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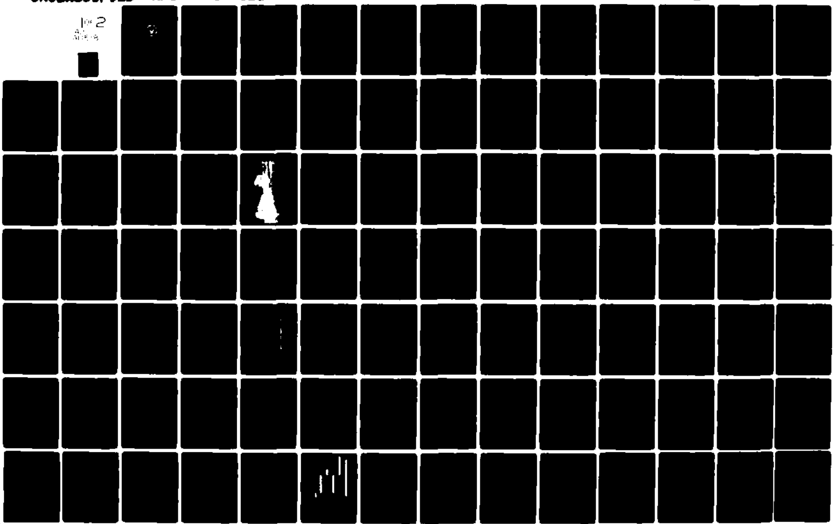

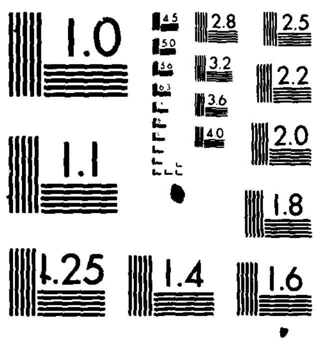
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

LONG RANGE
LOGISTICS PLANNING FOR VHSIC
(VERY HIGH SPEED INTEGRATED CIRCUIT)
COMPONENTS

by

Ronald Passmore Reed

December 1981

Thesis Advisors: L. G. Pollard
J. W. Creighton

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Prepared for:
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capability, these high density circuits will require much less power and space, but will yield far more reliability and performance. Because high technology developments have historically demonstrated less than optimum systems' readiness/availability due to degradations in logistics support, human factors and quality assurance, there has never been such an auspicious opportunity to realize the synergistic effects of integrated logistics planning on the implementation of VHSIC technology in weapons' design. This thesis explores that possibility and recommends specific actions for effective weapons systems' management.

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Long Range Logistics Planning
for VHSIC (Very High Speed Integrated Circuit) Components

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The Department of Defense is stimulating the research and development of vastly more complex and capable microelectronics to produce advance, militarized components in a timely and affordable manner. Through a six-year tri-service VHSIC (Very High Speed Integrated Circuit) Program that began in 1979, it will develop a radically new technology base for low cost, high throughput integrated circuits. Approaching a systems-on-a-chip capability, these high density circuits will require much less power and space, but will yield far more reliability and performance. Because high technology developments have historically demonstrated less than optimum systems' readiness/availability due to degradations in logistics support, human factors and quality assurance, there has never been such an auspicious opportunity to realize the synergistic effects of integrated logistics planning on the implementation of VHSIC technology in weapons' design. This thesis explores that possibility and recommends specific actions for effective weapons systems' management.

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I. INTRODUCTION

A. GENERAL

Perhaps the most powerful technological influence in defense electronics in the last half of the 20th century will be the VHSIC (Very High Speed Integrated Circuit) Program for the Department of Defense (DoD). To be administered and monitored by all three services (Figure 1-1), the program will have cost over a quarter billion dollars when fully implemented (1981 dollars), but will conservatively save an estimated ten times or more that amount. Not only will the resulting devices cost much less than their previous generation's conventional counterparts, but every aspect of operation--power required, reliability, performance--will be enhanced.

By the mid-eighties, it is anticipated that vastly more complex and capable semiconductor integrated circu[illegible]s) will flow from the program. They will be designed s[illegible]cally to handle military tasks, such as detecting, recognizing and classifying targets through "noise." They will be used in new systems or "technology injected" into existing ones. Bulky "black boxes" will shrink to the size of one or two "chips" or a single circuit board. Fault tolerance, with built-in test capabilities and "self-repair" circuit redundancy, will enhance weapons systems reliability while, at the same time,

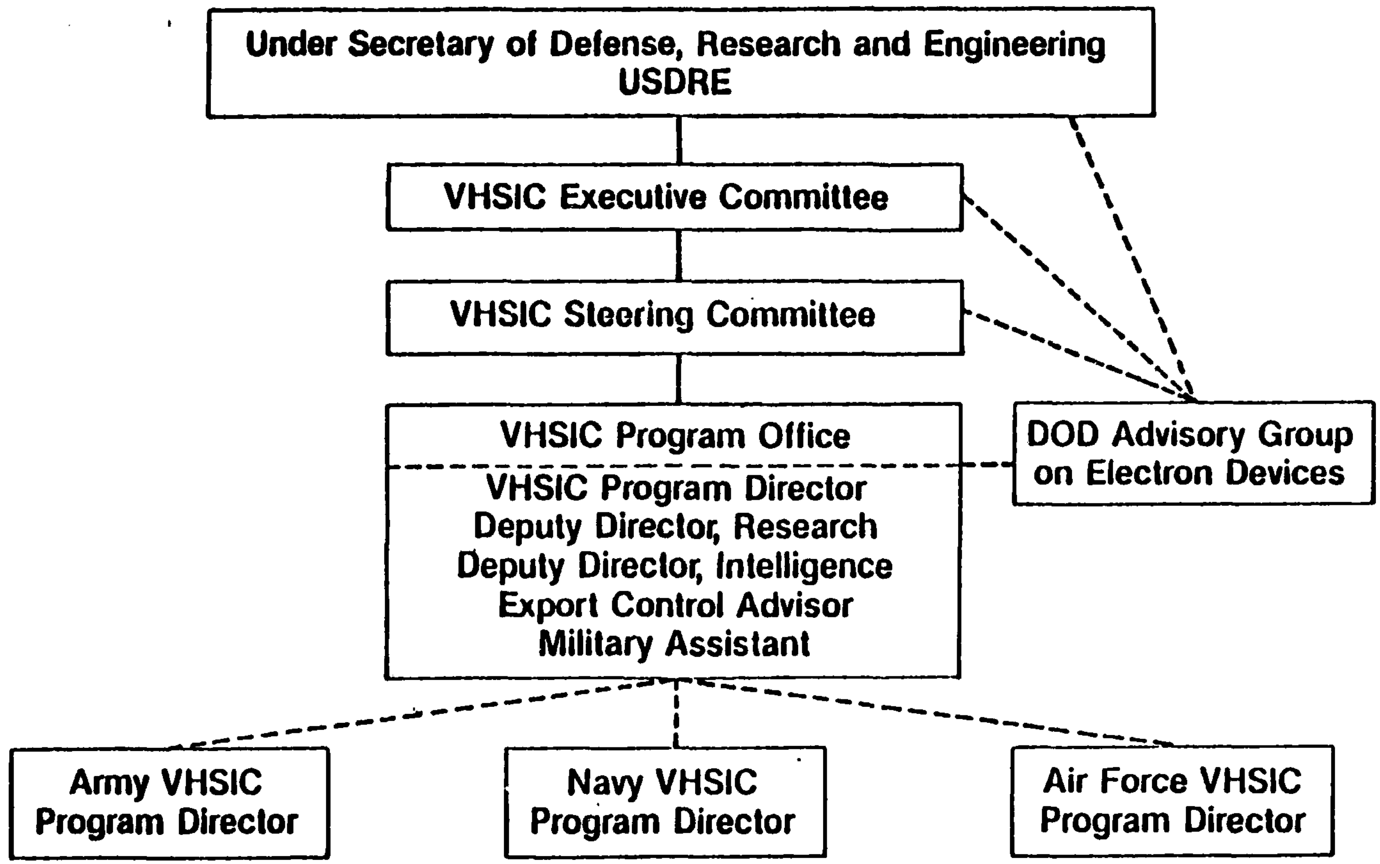


FIGURE 1-1: VHSIC MANAGEMENT STRUCTURE [Ref. 10]

reduce maintenance time, manpower requirements and total costs. Based upon the current commercial VLSI (Very Large Scale Integration) development of ICs characterized by high density, low cost, high reliability, standard chip sets and self diagnostics, VHSIC applications will additionally concentrate on the military considerations of radiation hardness, thermal tolerance and high throughput rate.

This breakthrough in microelectronics technology has come at a time when the search for more exacting technical triumphs has yielded a trend that reflects a lineage of weapons systems in which each generation of planes, tanks, missiles and ships costs between two and ten times more in constant dollars than the previous one. In nearly every instance, some have charged, designers have pushed technology as the solution to American military problems, without distinguishing between the innovations that simply breed extra layers of complexity and those that represent dramatic steps toward simplicity and effectiveness. As a result, the cost of military equipment keeps going up, the numbers of units in inventory goes down, and the reliability of each unit becomes open to serious question. [Ref. 5]

Perhaps the most vivid indicator of the DoD's increasing reliance on high technology weaponry is the continued reduction in the number of weapons platforms procured each year. In the aviation community, for example, the acquisition of fighter aircraft has decreased from 3000 a year in the mid-fifties, to about 400 a year in the late seventies, and to fewer than

230 in the FY-82 budget. Incident to the burgeoning technical complexity of the aircraft during this time, the cost of these first-line fighter planes rose by a factor of 100 (measured in constant dollars). The cost per fighter for avionics increased from about $3K to approximately $2.5M, while the cost for engines escalated from about $40K to over $2M. [Ref. 5]

This trend toward fewer, more complex units has been a compulsory by-product of the simultaneous reductions in manpower and increases in costs associated with using technology to compensate for an assumed manpower/machine imbalance with a potential adversary. It has not only had a significant effect on the total numbers of weaponry in the force, but also had a dramatic impact on the effectiveness or mission capability of those units.

Early in 1980, for example, Harold Brown (then DoD Secretary) issued a paper that compared the reliability records of a dozen different aircraft models. One measure of reliability or readiness was the proportion of time that the planes were not mission-capable because they needed repairs or lacked spare parts. The not mission-capable rate for the relatively simple A-10 was about one third, whereas the rate for the very complex F-111D was nearly two thirds, indicating a generally consistent connection between high complexity and low reliability. [Ref. 5]

Because this trend to push the state-of-the-art technology to the maximum performance levels has precipitated a

smaller defense force with questionable readiness rates, more and more attention is being focused upon improving the reliability, maintainability, testability, repairability, and supportability of weapons platforms and their systems. In a report to Congress detailing problem areas, Comptroller General Elmer B. Staats said that:

> The United States' ability to fight a war may be severely hampered because many of the aircraft, ships, tanks, ordnance and other systems the armed forces must use are suffering from numerous problems...While these systems may have the capability to perform their missions, it is often of little value because not all the systems can be adequately operated, maintained or supported. [Ref. 1]

Likewise, the General Accounting Office (GAO) has reported on system problems in the past. During the 1979-1980 time frame, it issued 44 reports on system degradation examples of equipment reported by the armed forces to be undependable and difficult to operate and support, ranging from the Navy antisubmarine warfare capability to DoD force management and Marine Corps amphibious readiness. Figure 1-2 illustrates the scope of this problem, indicating that equipment complaints have encompassed hardware, electronics, test equipment as well as a lack of adequately trained and experienced operators and maintenance personnel.

In investigating these trouble areas, the GAO found that many past problems could be traced to the DoD systems acquisition processes, particularly in early phases when the design is set, where "the pressure to attain specific performance goals (such as speed, range and firepower), within tight

GAO EQUIPMENT COMPLAINTS

Investigators cited these examples of military equipment reported by the armed services to be undependable and difficult to support and operate:

HUGHES TOW antitank missile system ground version - Battery power supplies are unreliable. As a result, missile launches were jeopardized or guidance was lost during flight. The Defense Dept. said the Army is procuring a new type of battery, and by also using TOW vehicle power conditioners, has eliminated the problem.

RAYTHEON / KOLLSMAN DRAGON antitank missile system - Component malfunctions plus human factor problems caused many of these missiles to miss the target Defense Dept. said there have been some component malfunctions, mainly defective thrusters, but these problems were detected prior to deployment and use and cannot be said to contribute to misses.

BELL AH-1 COBRA attack helicopter - Main rotor hub has significant reliability problems due to frequent failure of feathering axis bearings.

SPERRY GYROSCOPE AN/SPG-55B guided missile control radar on surface warships - *Low reliability, replacement parts shortages* and inadequate operator and maintenance training are affecting operational availability.

NORDEN SYSTEMS AN/SPS-40 air search radar on surface ships - High failure rates of some parts, long time to receive replacement parts and inadequate number of trained technicians lead to operational availability problems.

LOCKHEED S-3A antisubmarine warfare aircraft - Low reliability of many key electronic components have caused low aircraft operational availibility rates.

Components that form expandable nozzles (turkey feathers) on afterburners installed on McDonnell Douglas F-15 aircraft engines - These engine parts are wearing out after about 15 hr. of use. They cost $1000 each and each F-15 aircraft has 30 of them.

PRATT AND WHITNEY F100-PW-100 engine in F-15 aircraft - Problems with reliability and durability, particularly in the hot section, have led to low operational availability rates.

AUTOMATIC TEST EQUIPMENT for F-15 aircraft - Problems include lack of adequately trained and experienced operators and maintenance personnel. There is some soft ware incompatibility and low reliability of the built-in test and avionics intermediate shop automatic stations. These problems degrade testing efficiency and ultimately degrade an aircraft's operational readiness.

STABILITY AUGMENTATION SYSTEM in Fairchild Republic A-10 attack aircraft - Problems with targeting on the first 201 aircraft and with vibrations and signal interruptions on the last 158 aircraft affect the aircraft's mission effectiveness.

FLIGHT CONTROLS IN A-10 aircraft - Clearance for the aircraft cables and controls is not sufficient and foreign objects may jam the controls. This condition may already have contributed to aircraft accidents.

FIGURE 1-2: GAO EQUIPMENT COMPLAINTS [Ref. 1]

time and cost constraints, have often led management to trade-off or otherwise not give adequate attention to long term ownership considerations." As a result, degradations in logistics support, human factors and quality assurance negatively impacted the readiness/availability of systems over the long run. [Ref. 1]

B. OBJECTIVE

In light of the growing list of equipment complaints about the operation and support of these new, high technology oriented systems, the GAO has sought guidance for weapons systems program managers that will lead to better maintainability and operations in the field. Indeed, some direction has already been issued in terms of policy directives and acquisition guidelines. Conceivably any attempt to incorporate into long range planning the impact of the DoD VHSIC Program has been limited or undeveloped, even though the implications of this VHSIC technology transfer process are both astounding and awesome.

Illustrating this fact, Klaus D. Bowers, vice president of electronics technology at Bell Laboratories, has pointed out that, even though the number of devices on an integrated circuit chip has typically doubled every year, his technicians can design a chip in the same amount of time year after year--in spite of the fact that, after five years, it has 32 times as many parts. [Ref. 11] Such accomplishments are indicative

of the impact of technology on the production of integrated circuits, bringing computer aided design techniques and modern manufacturing equipment and processes together. The thrust of this current renaissance in the development of VHSIC components, primarily sponsored by the need for advance military requirements, will have direct and consequential impact on weapons systems management.

It is therefore the objective of this thesis to identify, from a logistics point of view, what recommendations should be made to a weapons systems program manager who will be introducing VHSIC technology into his weapons systems design or redesign. Since VHSIC technology will bring about extensive changes in the systems hardware itself, a fresh approach to the supply support maintenance plan, support equipment, personnel and training, and the like will be required. It appears to this writer that the conventional approach will not be adequate.

C. METHODOLOGY

The approach to the information collection process consisted primarily of extensive liaison with Mr. Lonnie Pollard, Logistics Manager in the Boeing Aerospace Company, where extensive resources are being dedicated to the research and development of VHSIC technology, applications, supportability and interoperability. In actively pursuing a systems engineering approach that has as its goal the achievement of a proper

balance between operational, economic and logistics factors, Boeing has set forth viable VHSIC logistics objectives designed to:

1. Establish military/industry dialogue

2. Identify key logistics research areas

3. Initiate coordinated military/industry logistics research which will impact the logistics statement of the MENS (Mission Element Need Statement), define optimum reliability goals, and specify application areas which will produce the greatest life cycle support benefits.

Because of the relative newness of the VHSIC Program, no information was readily available from technical texts or journals. Additional information was therefore sought from current periodicals, VHSIC program managers and engineers working in this field.

In the area of logistics management, information was acquired from existing DoD directives, which concern the acquisition and management of integrated logistics support for systems and equipment, as well as from lecture notes used in the Naval Postgraduate School course MN-4310: Introduction to Logistics Engineering.

D. ORGANIZATION

This thesis is designed to provide a weapons systems manager with an introduction to the VHSIC program, an overview of the logistics element of weapons systems management, a

discussion of VHSIC idiosyncracies in the context of their potential applications, as well as conclusions and recommendations for VHSIC implementation.

Chapter I describes the urgency for recognizing the impact of technology and weapons systems complexity upon the overall military readiness and effectiveness rates. It sets the stage for identifying the need for long range logistics planning for VHSIC components and sets forth the objective and methodology of this thesis research.

Chapter II provides a synopsis of the VHSIC Program for those not familiar with its origin and progress to date. After the past and present program objectives are highlighted, some of the many planned and projected VHSIC applications are enumerated to illustrate the tremendous scope of this next generation of microelectronics.

Chapter III reviews the present approach to weapons system design and support, emphasizing the critical interfacing actions which, in the context of their life cycle planning, impact upon the reliability, maintainability, testability, repairability and supportability of weapons platforms and their systems. The role of integrated logistics and the periods of systems life cycle support are stressed.

Chapter IV discusses the implications of implementing VHSIC technology within the framework of the conventional ILS approach. Since GAO found that degradations in <u>logistics support</u>, <u>human factors</u> and <u>quality assurance</u> negatively

impacted the readiness/availability of systems over the long run, each of these areas is evaluated as to its impact on the VHSIC Program.

Chapter V summarizes the current status and points of comparison of the DoD VHSIC Program and ILS approach to weapons systems management. It lists seven recommendations for systems and project managers who may be introducing VHSIC technology into weapons system design or redesign. It also lists three recommendations for future research projects related to the DoD VHSIC Program.

II. VHSIC PROGRAM

A. BACKGROUND

DoD has implemented its VHSIC Program to develop and produce in a timely and affordable manner advance integrated circuits for application in future military systems. Possibly as early as the mid-eighties vastly more complex-function microcircuits will be introduced into areas where existing systems were judged to be too large, used old technology and/or demonstrated urgent updating need. The anticipated size-weight-power shrinkage will enable DoD, the aerospace primes and the systems specialists to project radical avionics improvements into fighters such as the F-15, F-16 and F-18 where onboard space is at a premium. The same advantages

will eventually apply to essentially all other major airframes, trading electronics for fuel and hard weapons.

The tangible benefits notwithstanding, however, perhaps the most pervasive impact of this program will be "the change in what for more than a decade has been the traditional and increasingly unsatisfactory relationship between defense system contractors and their commercial semiconductor suppliers." [Ref. 1] Fundamentally, this relationship, between DoD and prime contractors on one hand, and the commercial manufacturers/suppliers on the other, had deteriorated seriously as early ICs became orders of magnitude more complex and caused the commercial suppliers staggering development costs for each new device. These costs were exacerbated by the similarly soaring costs of introducing new-processing technologies on larger and larger IC wafer substrates that grew from one to five inches in diameter between 1965 and 1980.

Concurrently, the explosive growth of commercial markets and the relatively shrinking significance of military and space programs had placed special purpose, military and space qualified devices into a minor category. Whereas defense and space applications had once been prime driving forces in the semiconductor technology and IC development, their share of the market shrank from over 70% to under 7% from 1960 to 1980. Most commercial suppliers could not (and did not) spend to develop low-volume, special purpose military devices because of limited resources. They concentrated instead on high-volume

applications such as memories and microprocessors which were saleable by the million to other commercial customers. Among them, only Texas Instruments and Westinghouse maintained dedicated military IC facilities.

In the late seventies, however, as the technology tide turned, large aerospace primes realized that they needed such capabilities to compete with new systems and invested heavily in new facilities. Their rationale was that, as the functional complexity of commercially available chips increased, their own ability to innovate and to compete was constrained. Systems manufacturers, such as E-Systems and Martin Marietta, felt compelled to make the necessary investment. Upon this tide, system suppliers then possessed both the expertise and the motivation to participate in an associate role with DoD because of the prospect of being able to add to their catalog new products which had been designed by experts in military-peculiar complex functions and whose design cost would be underwritten by DoD.

In this context the VHSIC Program was launched in June 1979, allocating a total of $225M initially (now up to $324M) to be expended over a six year period, through four distinctly identifiable phases and under the management control of OUSDRE (Office of Under Secretary of Defense for Research and Development). Primarily focusing on the development of microcomputers, signal processors, radars and sonars, this effort will attempt to make VHSIC circuits appear in the operational

inventory at the earliest possible time. To do this, the joint DoD/Systems manufacturers have been required to:

1. Make circuits available
2. Make manufacturing equipment available
3. Provide second sources for available circuits
4. Cause VHSIC to be designed into systems
5. Disseminate information within the program, to other potential users and, at the same time, withhold it from the enemy. [Ref. 9]

A brief description of the VHSIC Program's historical priorities and current emphasis follow this introductory background review. However, an indepth overview of VHSIC's role in defense technological development is provided in Appendix A, describing the DoD Program, examining the critical policy issues and providing examples of future VHSIC applications.

B. HISTORICAL PRIORITIES

The great enthusiasm among the systems and most semiconductor suppliers for the VHSIC Program has been due in part to how this program has accelerated their previous corporate timetables by at least two or three years. For some it has additionally served to orient research efforts to specific objectives and timetables. With VHSIC, devices developed during the effort will be made available to all interested defense contractors. Conversely, without VHSIC, custom-design microcircuits developed by one company would have been available

only for its own systems, while smaller companies would not have had access to such devices at all, thereby serving to reduce and limit competition and component availability.

Although the VHSIC Program is contributing only a modest increase in total U.S. funding to advance microelectronics technology, the DoD effort is providing a big impetus by setting specific objectives and timetables to meet defense systems needs. Larry Sumney, DoD VHSIC Program Manager, outlined these factors in the first major program review held 15 June 1981. Historical VHSIC priorities have included:

1. <u>Lithography for Small Feature Size</u>

Phase 1 called for achieving devices with minimum feature sizes of 1.25 microns (where one micron is one millionth of an inch), compared to the 3-5 micron sizes now being achieved in advanced designs. Phase 2 was to achieve 0.5 micron dimensions if possible, or at least 0.8 micron sizes. In exemplifying this phenomena, if a map of the entire United States were printed using 0.5-micron-wide lines on a 20-inch wide sheet of paper, it would be possible to show every individual street in the country. [Ref. 11] Such miniaturization achievements implied by the name microelectronics, will be far beyond the current state-of-the-art capability shown in Figure 2-1, culminating in a systems-on-a-chip device capable of incorporating up to one million transistors.

2. <u>Design, Architecture, Software and Test</u>

Recognizing the trend toward smaller feature sizes and growing chip complexity, companies like General Electric

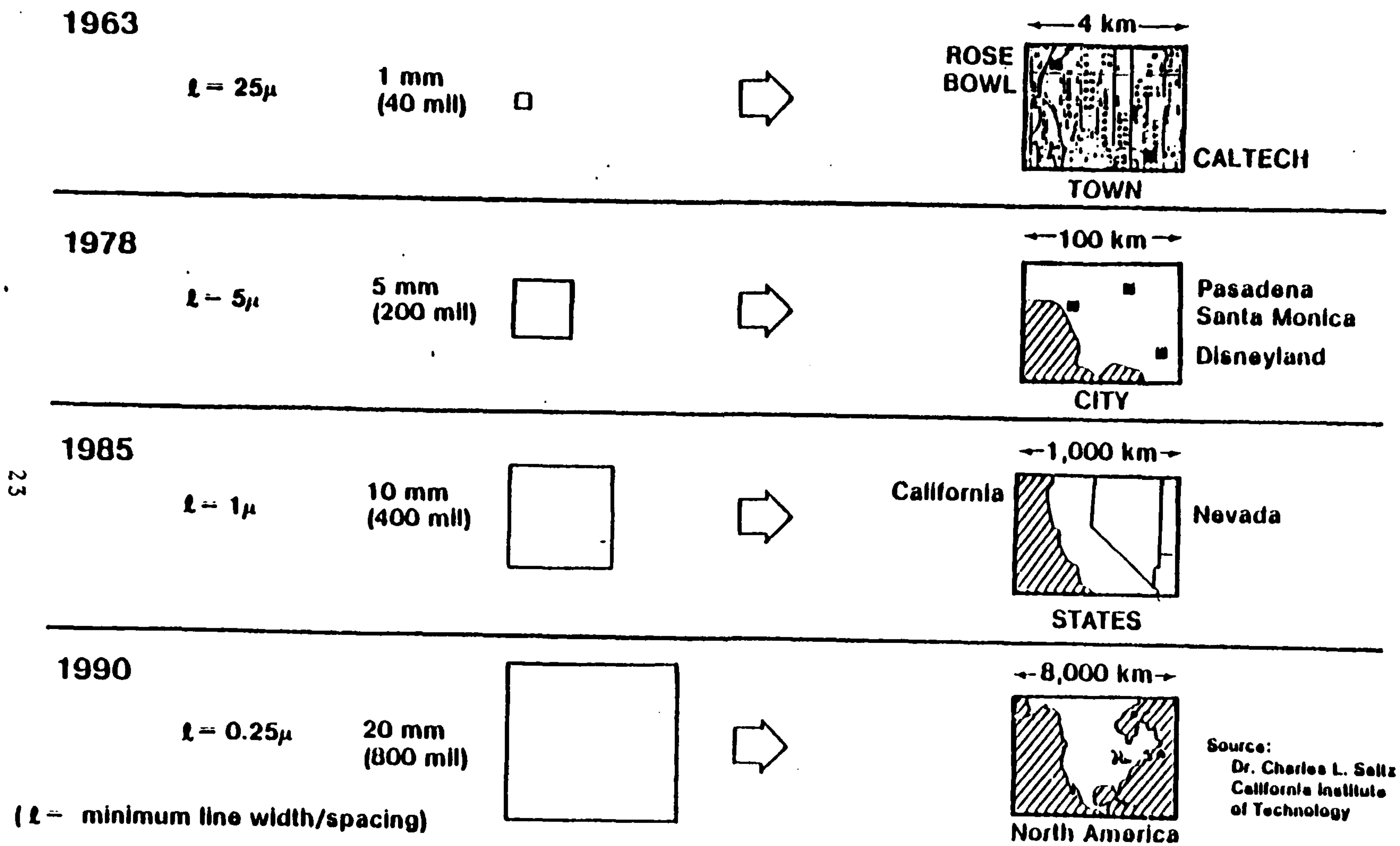


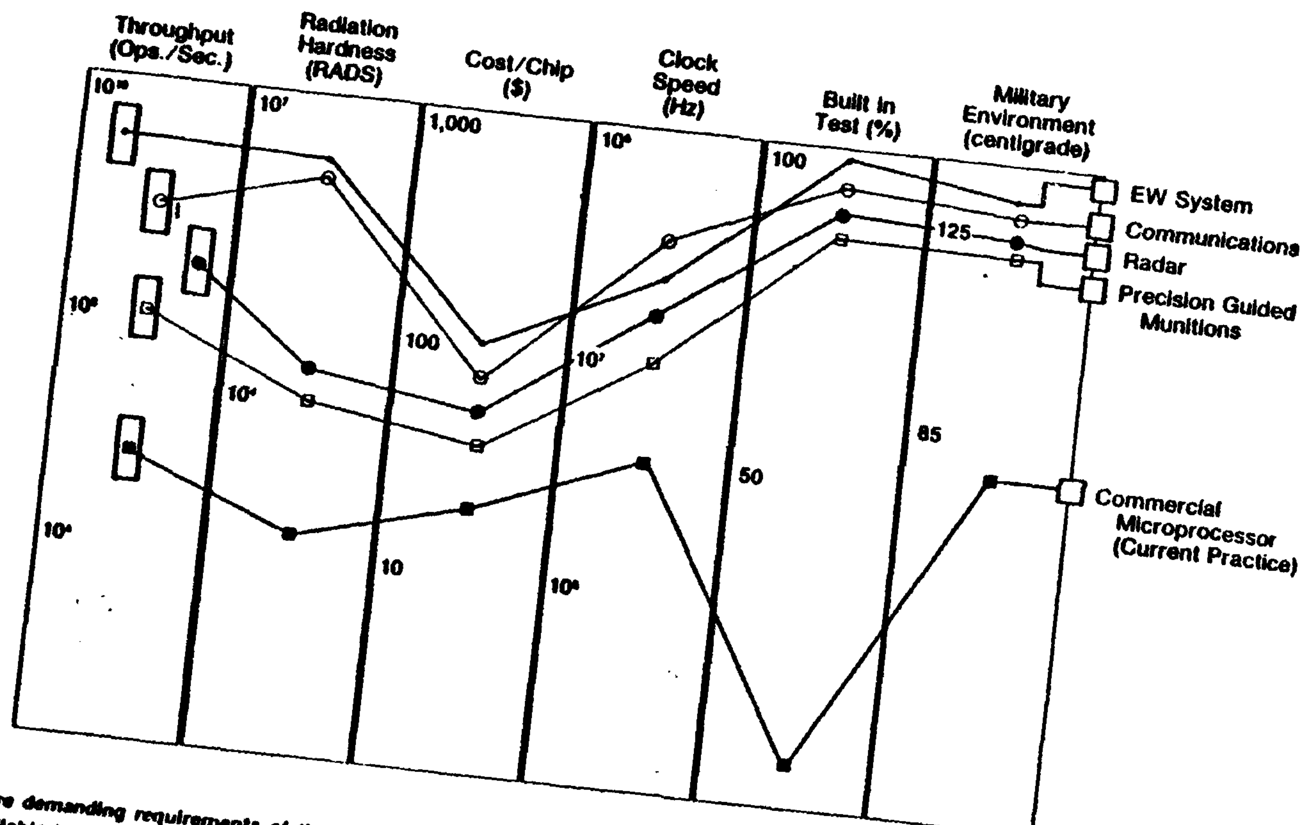
FIGURE 2-1: DENSITY AND COMPLEXITY AVAILABLE FOR VHSIC's SMALL FEATURE SIZE

(Courtesy of Boeing Aerospace Company)

sought to develop an architecture that would be "technologically transparent;" i.e., it tried to develop an architecture for a complete functional subsystem that could eventually be fabricated conveniently, for example, on several chips using 1.25 micron devices; and that in the nearer term could be made on a larger number of chips using 3-micron feature size devices in a "nested-design." In this way, the investment in design architecture could be preserved and used in later generations of more complex devices. Equally important, the newer, more functionally complex microcircuits could be substituted for earlier generations in existing weapons systems and in new designs wi ı minimal impact, especially on weapons systems software. This "bottom-up" approach was aimed at developing microcircuit design commonality to meet a wide variety of applications. [Ref. 7]

3. <u>Speed for Signal Processing</u>

Going beyond simply increasing the functional complexity on a chip, DoD sought microcircuits capable of performing complex signal processing functions at very high near-real-time speeds; hence, the name "very high speed integrated circuits." Design goals were set as a product of the number of gates per square centimeter of chip area and the operating speed of the gates--a more realistic measure of microcircuit utility for the military functions reflected in Figure 2-2. Program objectives specified a processing or throughput rate of 5×10^{11} gate-Hz./sq. cm. for Phase 1 and 1×10^{13} gate-Hz./sq. cm. for



More demanding requirements of the Defense Dept. for several basic types of applications, that go beyond functional complexity now available in commercial microprocessors, are shown. Higher processing speed to perform peculiarly military functions of detecting and discriminating targets of interest in presence of clutter background is one of the most crucial requirements.

FIGURE 2-2: REQUIREMENTS FOR MILITARY PECULIAR FUNCTIONS [Ref. 11]

Phase 2, making the speed and density objectives for Phase 1 roughly a five-fold improvement over the best then-available technology, and for Phase 2 approximately another 20-fold improvement over Phase 1--or a 100-fold improvement over the best 1978 state-of-the-art when the program began.

4. Getting the Program in Place

The developments from company funded programs before the start of Phase 1 raise the question of whether at least the initial objectives of the VHSIC Program would have been achieved without a DoD-funded effort. If the objectives of DoD were to demonstrate that a chip with the required Phase 1 speed and density could be fabricated, without being designed specially to perform a useful military function, there is no doubt that at least some semiconductor and defense systems houses would have achieved this portion of the program's objectives on their own. The unknown factor, therefore, is when this would have taken place--probably not soon enough to keep a competitive edge on foreign competition from Japan or the Soviet Union.

C. CURRENT EMPHASIS

VHSIC objectives have presented the semiconductor manufacturers with a host of challenges in the processing area as well as the prospect of heavy expenditures for the equipment needed for the new processing technologies. In implementing these new requirements, they have gained extensive experience

in increasing the use of computer-aided design (CAD) to intensify the use of design automation (particularly in the design of low-volume products) and in shifting some of the design burden from the device manufacturer to the user to reduce the amount of engineering time they must commit to new product development. It is anticipated that vastly improved and perhaps wholly new kinds of manufacturing equipment and processes will be needed for the volume production of advanced microcircuits embodying submicron features such as those planned in Phase 2 of the VHSIC Program.

While these technology investigations and research efforts have been proceeding, DoD has also been gaining experience in this endeavor and finetuning its program. It has exploited the technology transfer process through procedures which allow VHSIC components to be quickly transferred from producers to users. At the same time, it has required the interoperability of VHSIC components with other systems, so that the increased effectiveness and utilization of VHSIC technology can be realized through design features which ensure that VHSIC circuits and other products are compatible and form a synergistic set of building blocks. As a result, four major issues have emerged to characterize the DoD program:

1. <u>System Technology Insertion</u>

In order to give the systems' designers and semiconductor manufacturers a direction on which to focus, a list of initial applications was compiled by the three services, identifying:

a. Current operational systems/equipments where VHSIC chips can be inserted to cost, size, volume and reliability advantage like that achieved by Boeing in Figure 2-3

b. Planned upgrades for systems/equipments in design that can use VHSIC

c. New VHSIC-derived functions that can be added to existing systems/equipments

d. New system/equipment capabilities that could exist because of VHSIC. [Ref. 10]

During the three-year Phase 1 effort, contractors will be required to design and fabricate brassboard chips capable of meeting some of these applications. Each contractor must develop chips or chip sets capable of meeting at least one weapon system requirement of each of the three services and, in the end, be in pilot production of the new complex-function chips. The present timetable calls for pilot production of such "super microcircuits" by late 1986. With potential application to 34 different weapons and subsystems, the six brassboard functions which won Phase 1 competition were:

a. Tactical fighter aircraft radar signal processor by Westinghouse

b. Electronic warfare signal analyzer/processor by TRW Systems

c. Multimode fire-and-forget missile guidance by Texas Instruments

d. Battlefield information distribution system by Hughes Aircraft

e. Electro-optional signal processor by Honeywell

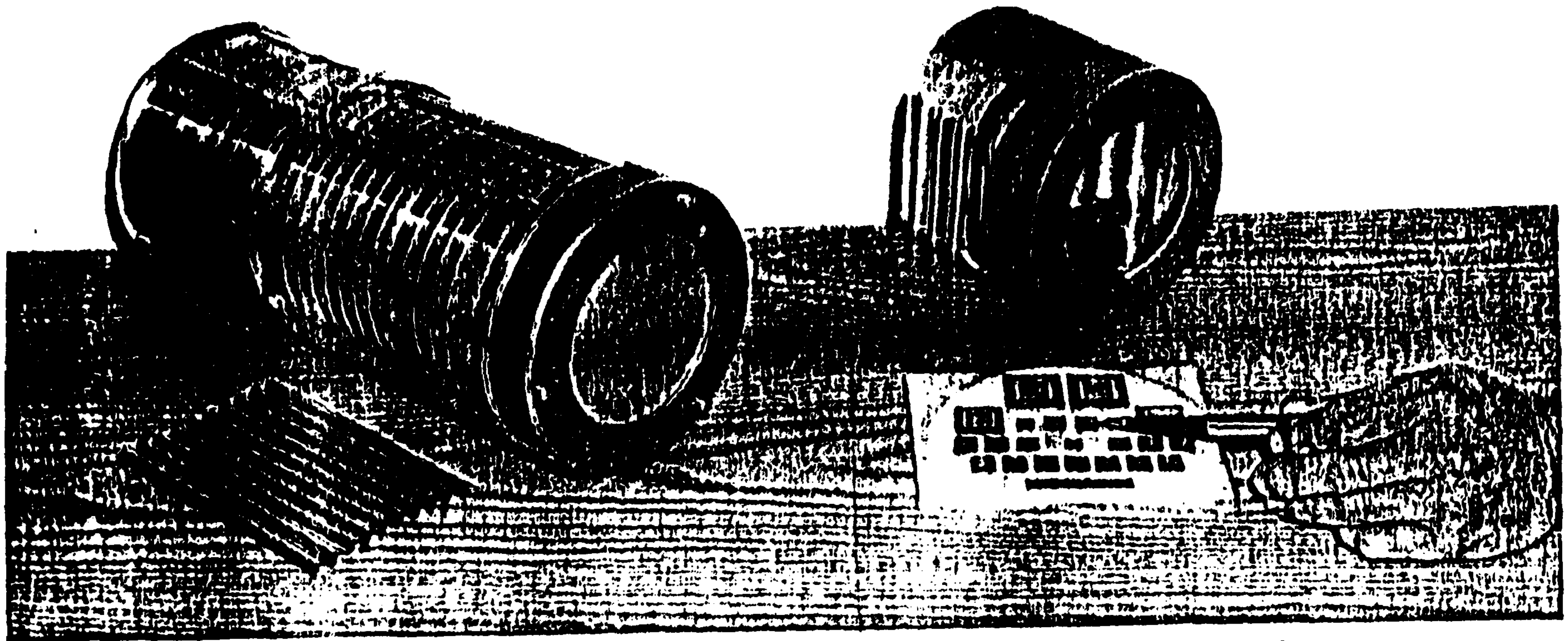


FIGURE 2-3: POTENTIAL IMPACT ON BOEING WASP AUTOPILOT

(Courtesy of Boeing Aerospace Company)

f. Acoustic signal processor by IBM [Ref. 7]

Where additional funds can be generated, other brassboard functions and chip sets (concentrating on microcomputers, signal processors, radars and sonars) will be exploited to take advantage of the momentum now in progress and maximize the use of VHSIC new as well as existing systems equipment.

2. Acquisition Policy

Now that more experience has been gained in how well contractors are meeting the performance established several years ago for devices with smaller feature size and corresponding high chip complexities, more selectivity can be exercised in the allocation of funds. For example, DoD's VHSIC Program Manager, Larry Sumney, believes that many projects aimed at improved lithography might be reduced in order to divert funds to other areas such as radiation hardness, fault-tolerance designs and built-in-test (BIT). [Ref 7]

3. Application Expansion

During the competition for Phase 1 awards, the nine Phase 0 contenders proposed a total of 70 different VHSIC brassboards that covered a broad spectrum of potential applications. Since only 6 of these were chosen, one for each Phase 2 contractor, there remains a number of potential areas for expansion to meet specific program needs. For example, DoD funded TRW for only eight of their fourteen proposed chips designed to build signal processors for a wide variety of applications, including electronic warfare, radar, sonar,

imagery and command and control. According to TRW, if support can be obtained for two additional chip types, they could fabricate a communications brassboard; or, if four other chip types are developed, it would be possible to build a distributed-architecture type general purpose computer. The possibilities are therefore readily available for additional chip sets which could offer tremendous benefit to VHSIC effort. [Ref. 7]

4. Maintenance-free Electronics

The fourth and final area receiving current emphasis expresses the commitment to ensure that systems/equipment emerging from the program not only are generations better in reliability and maintainability, but also meet interoperability requirements (when interfacing with other systems/equipment) so as not to jeopardize the reliability/maintainability levels achieved. Additional research is being dedicated to obtaining:

a. Radical improvements in systems availability, usability and affordability

b. High integration level which can cause a 10 to 100:1 improvement in reliability

c. Built-in-test (BIT) which could greatly simplify maintenance procedures and reduce Life Cycle Costs (LCC)

d. Fault tolerant designs which can offer another order of magnitude of improvement in reliability as well as further LCC reduction

e. Environmental hardening which will ensure that the system will work when and where it is needed [Ref. 10]

D. SYSTEM ECONOMICS

In order to sustain the momentum of the historical objectives and properly implement the intent of the current objectives, attention is now being focused beyond acquisition of specific performance characteristics to that of achieving an overall affordable product. Although the dramatic economics of large scale integration are widely understood, the impact of integrated circuit technology on the cost of maintaining an effective military force understandably goes beyond the cost of the product itself. The costs of these integrated circuits and their assembly into subsystems is generally small relative to the aggregate cost of product qualification, acceptance testing, packaging, documentation, special test equipment, logistics and operational support, and life cycle costs of the host system. Apart from the initial procurement costs, these system support costs typically include the incremental cost of power, space, testing, maintenance, etc., and generally far exceed the total procurement costs of the integrated circuit subsystem.

Exemplifying this recent development, the Naval Air Development Center in Warminister, Pennsylvania, in studying ways to introduce VHSIC technology into weapon system design, will establish requirements for a meaningful demonstration of the application of VHSIC to airborne weapons systems, analyze the results, and evaluate the impact on weapons system performance as well as life cycle costs. Requirements for readiness

testing of VHSIC subsystems will also be determined and the feasibility of improving software development tools will also be studied, so as to raise software productivity to a level commensurate with the design flexibility expected from VHSIC products. User requirements for interface to system level computer aided design will be determined and functional design specifications produced.

In addition, the Naval Surface Weapons Center in Dahlgren, Virginia, has undertaken a project to improve the maintainability, testability, repairability, reliability, and supportability of the products from the VHSIC Program. Participating in the evaluation of issues which are prepared by industry response to the VHSIC request for proposals, it will research and identify issues in supportability, testability, reliability and maintainability that directly influence, or are influenced by, VHSIC technology.

The importance of reducing high operation and support costs is apparent, but how is this accomplished? What has been the conventional approach to weapons system design in terms of balancing the desire for high performance with the need for high supportability, all within given cost constraints? The following chapter addresses these and similar questions on the planning, acquisition and use of complex systems like those associated with VHSIC technology.

III. SYSTEMS DESIGN/SUPPORT INTERFACE

A. A SYSTEMS APPROACH

Experience has demonstrated that the successful planning, acquisition and use of complex systems requires a "systems approach" which recognizes the interrelationships that tie a system together. In its application, the systems approach requires that a system be planned and designed as an entity so as to satisfy the needs of the user, especially with respect to evaluating and optimizing its costs and benefits. In addition, it also requires a rational methodology for optimum implementation and operation, considering such factors as:

1. The System Life Cycle (SLC)--its phases, activities and duration
2. Cost-effectiveness of the system over its operational life
3. Operational needs, technology, cost, schedule, operating and support environments, as well as constraints on all of these
4. User-producer relationships over the SLC
5. System and subsystem interfaces--both internally and with the operational and support environments

In the total systems approach, represented by Figure 3-1, it is essential that both the Operational System and the Support System, as well as their hardware and software subsystems and interfaces, be considered from the beginning.

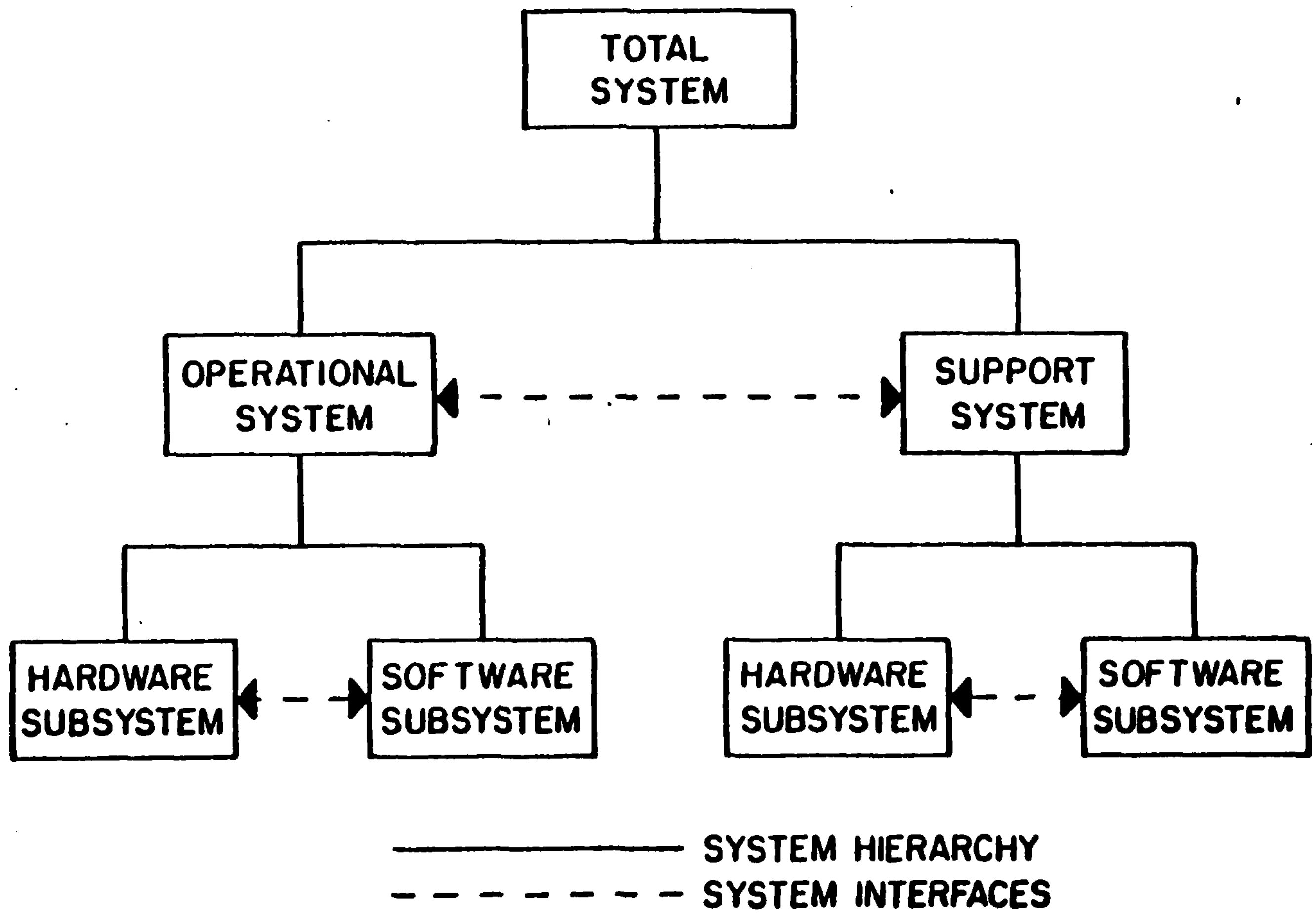


FIGURE 3-1: THE TOTAL SYSTEM CONCEPT [Ref. 8]

Typically, early attention is focused on the Operational System with Support System concepts and design left for a later phase of the life cycle. Likewise, software considerations are often deferred until after hardware design is well along, many times resulting in severe interface problems, reduced system effectiveness, increased cost, and/or significant design, maintenance and support restrictions.

To understand how this process takes place, it is beneficial to review the characteristics of the systems approach as reflected in the SLC, especially with respect to the Design and Support Phases and their interface.

B. THE SYSTEM LIFE CYCLE

Basic to the systems approach method is the concept of the SLC or "conception to grave" viewpoint, representing the phases through which any system passes and the different activities which take place during these phases. Such activities are of concern to both the users and the producers of the system. The user is concerned with stating and developing the needs and concepts for the system as well as for the operation and support of the system. The user provides the input requirements to which the producer designs. The producer, on the other hand, is concerned with translating the user's needs into the design, production and installation of a system which meets these needs and which can be operated and supported in a cost-effective manner.

Illustrated in Figure 3-2, the SLC begins with the Planning Period, during which the need for a new system is verified and system concepts are formulated. The operational environment and resources available are considered, thus limiting the variety of possible solutions. System feasibility is then determined by consideration of operational, technological, economic, political, legal and other aspects. Although this process is primarily the responsibility of the system user or customer, seldom is it accomplished without the help of the producer, or commercial contractor/government hardware command. At the end of this period, the system will have been defined by a set of requirements to meet the operational needs, thereby justifying further development.

Primarily the responsibility of the producer, the Acquisition Period includes the design, test, evaluation, production and installation of the system. It is during this period that the Design Phase evaluates the cost-effectiveness characteristics which were specified in the previous Planning Period. As they are tested and verified, some redesign or modification of the system is often made. At the end of the design effort, the specifications for the system that were previously agreed upon by the user and the producer are demonstrated or modified as a result of cost-effectiveness evaluation. The effectiveness values and cost estimates (e.g., projected Operational Availability/Mission Capability and Support Costs) are hereby accepted by both parties, and system deployment is initiated.

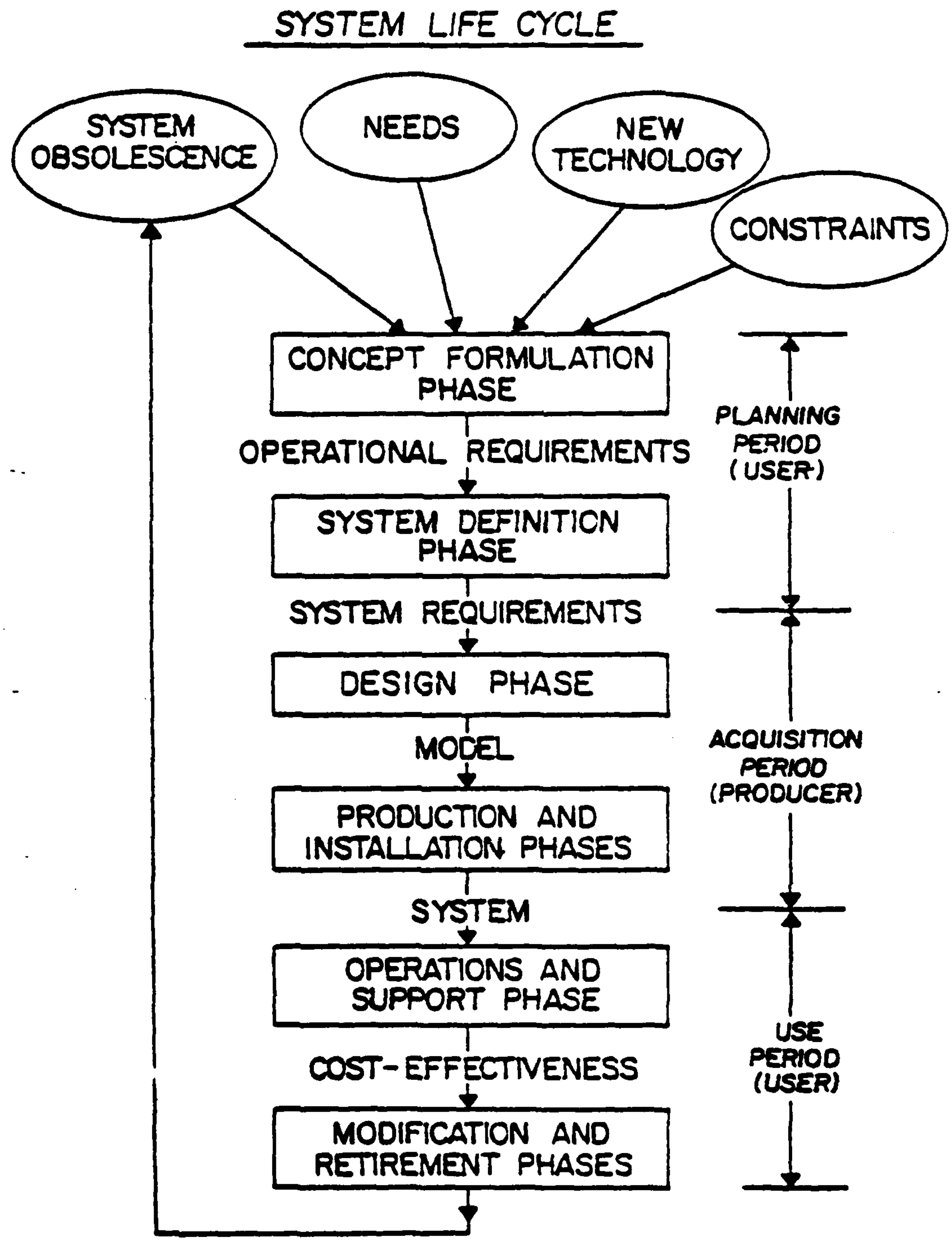


FIGURE 3-2: THE SYSTEM LIFE CYCLE [Ref. 8]

With Production and Installation Phases underway, responsibility for the operation and support of the system is then returned to the user.

The Use Period consists of those activities and resources required to operate, support, maintain and finally retire the system. This would include a periodic updating or improvement to prolong its life and/or to meet changing requirements. Thus, the cycle is completed where it began, with the user, leading to the next generation of new requirements and new life cycles to replace the ones which are no longer cost-effective to operate and support.

C. THE DESIGN PROCESS

The Design Process is the fundamental sequence of activities used for making design decisions or tradeoffs in each stage of the SLC. As the life cycle progresses from the recognition of a need through planning and design, the information generated by repeated application of the design process reduces uncertainty or risk concerning the desired system and its attributes, permitting the commitment of increasingly larger quantities of resources to the acquisition and operation of the system. Planning design, engineering design, industrial engineering and design of operations become meaningful in the context of the matrix of Figure 3-3, illustrating what experienced observers have found to be a distinct pattern of events which is repeated from project to project. This

					DESIGN PROCESS							
					GATHER AVAILABLE INFORMATION	FORMULATE VALUE MODEL	SYNTHESIZE ALTERNATIVE SOLUTIONS	ANALYZE AND/OR TEST	EVALUATE	DECIDE	OPTIMIZE	COMMUNICATE
SYSTEM LIFE CYCLE	PLANNING	SYSTEMS ENGINEERING		CONCEPT FORMULATION								
				SYSTEM DEFINITION								
	ACQUISITION		DESIGN	PRELIMINARY DESIGN								
				ENGINEERING DEVELOPMENT								
				DETAIL DESIGN								
				TEST AND EVALUATION								
				PRODUCTION DESIGN								
		PRODUCTION AND INSTALLATION										
	USE	OPERATIONS AND SUPPORT										
		MODIFICATION AND RETIREMENT										

FIGURE 3-3: THE LIFE CYCLE/DESIGN PROCESS MATRIX [Ref. 8]

pattern exhibits both a vertical structurem called the SLC, is characterized by a sequence of phases and stages, with each stage terminated by a decision milestone; and each stage of the vertical structure is characterized by a horizontal structure that displays a repeated, fundamental sequence of activities known as the Design Process.

The Design Process is germane to all SLC periods and phases. During the planning and design, this process is concerned with optimizing the system design and effectiveness for anticipated operating conditions. During production and installation, it is concerned with optimizing production and distribution. During use, it is concerned with optimizing the operation and support of a given system. In all of these applications, both the producer and user of a system must possess a capability to apply the Design Process and understand the implications of the interface requirements illustrated in Figure 3-4.

This responsibility is perhaps most acute in the Design Phase of the Acquisition Period when the tradeoffs of costs and benefits/effectiveness are being determined. Such cost-effectiveness analysis provides a conceptual framework and methodology for the systematic investigation of alternatives. It enables the user to choose the preferred alternative out of many approaches by relating the cost of each alternative to its effectiveness or level of mission fulfillment. By

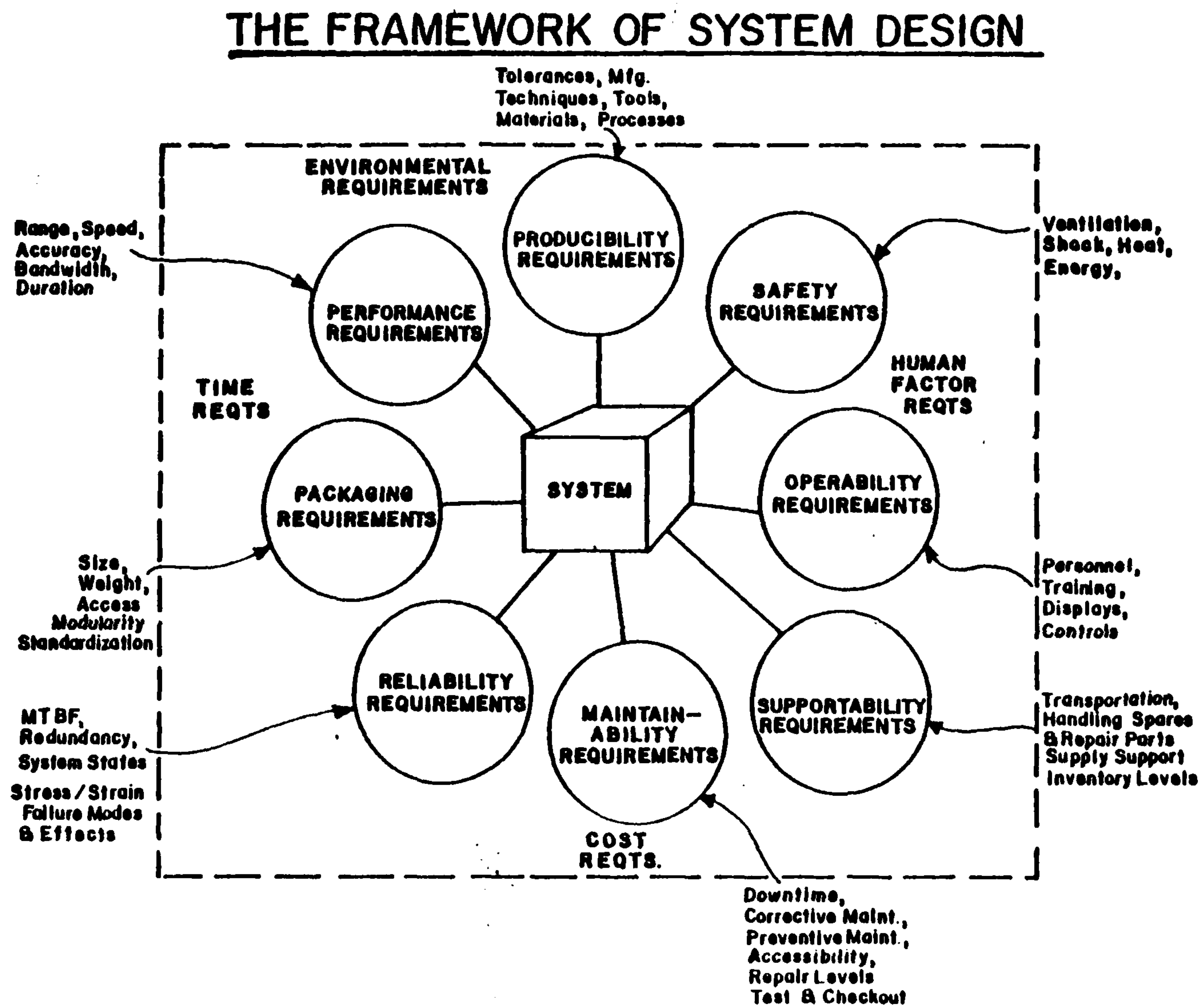


FIGURE 3-4: THE FRAMEWORK OF SYSTEM DESIGN [Ref. 8]

applying this analysis procedure, it becomes possible to select the optimal alternative for achieving the goals defined within the allowed constraints.

Of these two elements, cost is easier to measure and handle because it can be expressed by a single, monetary value, usually in terms of the Life Cycle Cost (LCC) of a system; i.e., all costs which are required during the complete SLC. The LCC method of system evaluation evolved as a response to budgetary considerations for operations and support activities where it was recognized that ownership cost generally exceeded procurement costs by several factors. Usually broken down into three categories, it includes costs for:

1. Research and Development--all costs accumulated during the conceptual, validation and full-scale development phases for systems engineering studies, design, drawings and specifications, development, prototype fabrication as well as testing, operation and support planning

2. Investment--all recurring and non-recurring costs of the production phase for tooling, test and support equipment, new facilities, training, manufacturing, labor, material and inspection

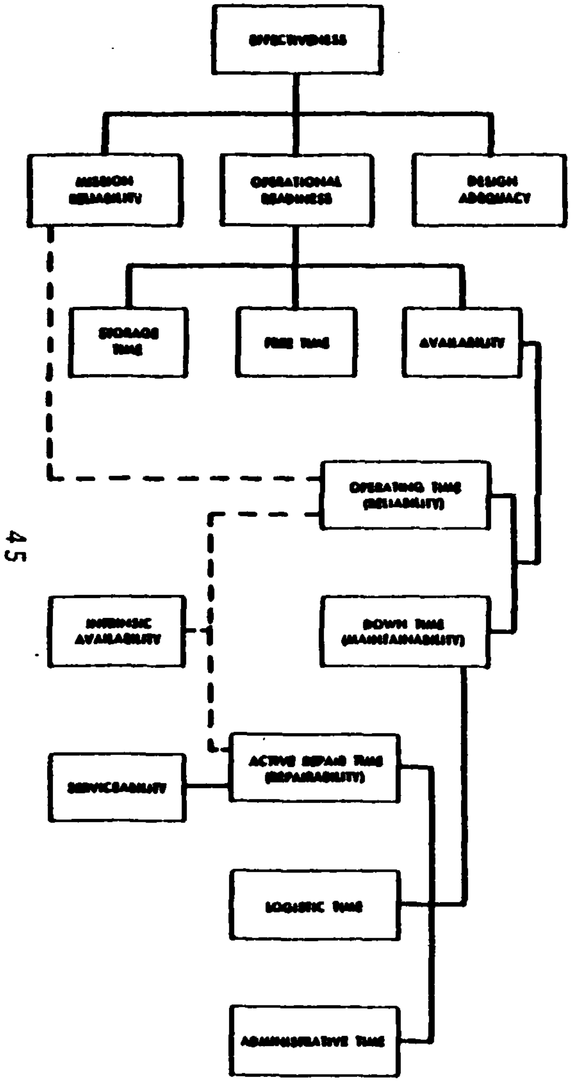
3. Operations and Support--all recurring costs spent on operating personnel, energy and operations for training, recruitment, retirement, salaries, housing, food, tools, utilities, etc.; and all costs of maintenance spare parts, provisioning, test and support equipment, training of support

personnel, transportation, documentation and facilities. Support cost will be addressed in more depth in a later section.

Systems effectiveness, on the other hand, is harder to deal with. It may be presented in terms of certain parameters which have clear-cut numerical representations, or in terms of non-quantifiable terms which are difficult to evaluate as a measure of the ability of a system to fulfill its mission in a specific environment. It should be evaluated continuously as system development proceeds in order to obtain an objective measure of the fulfillment of system needs. Illustrated in Figure 3-5, these concepts are primarily concerned with system performance, availability and dependability, factors which have strong relationships with implemented logistic policies and which involve system operating time, or reliability, and system down time, or maintainability.

D. THE SUPPORT PROCESS

In developing the systems approach to the management of complex systems, it was noted that consideration must be given to both the Operational System and the Support System. Each has a set of integrated and interrelated elements organized to perform designated functions in order to achieve desired results through their respective hardware and software subsystems and interfaces. Manifested in the SLC, periods and phases of this concept were presented to be fundamental



DEFINITIONS OF CONCEPTS

System Effectiveness is the probability that the system can successfully meet an operational demand within a given time when operated under specified conditions.

System Effectiveness (for a one-shot device such as a missile) is the probability that the system (missile) will operate successfully (kill the target) when called upon to do so under specified conditions.

Reliability is the probability that the system will perform satisfactorily for at least a given period of time when used under stated conditions.

Mission Reliability is the probability that, under stated conditions, the system will operate in the mode for which it was designed (i.e., with no malfunctions) for the duration of a mission, given that it was operating in this mode at the beginning of the mission.

Operational Readiness is the probability that, at any point in time, the system is either operating satisfactorily or ready to be placed in operation on demand when used under stated conditions, including stated allowable warning time. Thus, total calendar time is the basis for computation of operational readiness.

Availability is the probability that the system is operating satisfactorily at any point in time when used under stated conditions, where the total time considered includes operating time, active repair time, administrative time, and logistic time.

Intrinsic Availability is the probability that the system is operating satisfactorily at any point in time when used under stated conditions, where the time considered is operating time and active repair time.

Design Adequacy is the probability that the system will successfully accomplish its mission, given that the system is operating within design specifications.

Maintainability is the probability that, when maintenance action is initiated under stated conditions, a failed system will be restored to operable condition within a specified total down time.

Repairability is the probability that a failed system will be restored to operable condition within a specified active repair time.

Serviceability is the degree of ease or difficulty with which a system can be repaired.

DEFINITIONS OF TIME CATEGORIES

Operating time is the time during which the system is operating in a manner acceptable to the operator, although unsatisfactory operation (or failure) is sometimes the result of the judgment of the maintenance man.

Down time is the total time during which the system is not in acceptable operating condition. Down time can, in turn, be subdivided into a number of categories such as active repair time, logistic time, and administrative time.

Active repair time is that portion of down time during which one or more technicians are working on the system to effect a repair. This time includes preparation time, fault-location time, fault-correction time, and final check-out time for the system, and perhaps other subdivisions as required in special cases.

Logistic time is that portion of down time during which repair is delayed solely because of the necessity for waiting for a replacement part or other subdivision of the system.

Administrative time is that portion of down time not included under active repair time and logistic time.

Free time is time during which operational use of the system is not required. This time may or may not be down time, depending on whether or not the system is in operable condition.

Storage time is time during which the system is presumed to be in operable condition, but is being held for emergency -- i.e., as a spare.

FIGURE 3-5: CONCEPTS ASSOCIATED WITH SYSTEM EFFECTIVENESS [Ref. 8]

to the understanding and use of the cost-effectiveness approach in decisions concerning systems planning, acquisition and use. It is during the system life cycle that the systems effectiveness characteristics are established, achieved, and/or modified for possible cost-benefit tradeoffs.

The advantages of the cost-effective analysis are perhaps most revealing in the area of support where the costs for logistics efforts in operating and maintaining systems and equipment far exceed acquisition costs. Consistent with the systems approach methodology, the term "integrated logistics support" or ILS has been used in reference to the Support System, focusing attention on the logistics engineer and logistician and their respective roles in the total systems acquisition process and SLC. In today's dollar-conscious environment, and with severe pressures on the federal budget, the users and producers emphasize the concepts of ILS as a systematic means of reducing costs while maintaining full capability to perform assigned roles and missions.

It is important to bear in mind, however, that ILS is not simply a cost-reduction idea. It is far more. ILS can be described as a systems approach which employs management techniques to optimize the tradeoffs among a set of engineering design alternatives. It involves an improved technical planning and predictive capability to ensure more "defense per dollar," requiring an increased emphasis on consideration of all elements of the logistics support system. In short,

ILS provides both the impetus and the opportunity for the logistics manager and specialist to apply their every capacity in working with systems and design engineering to meet the changing user goals. [Ref. 8]

1. The Initiation of ILS

Historically, support management was seen as a post-production function where consideration of operational factors was accomplished to the exclusion of early support management planning. Acknowledging the shortcoming of this mode of operation, DoD Directive 4100.35, entitled "Development of Integrated Logistics Support for Systems and Equipment," was issued in June 1964 to assign military agencies the responsibility for devising and implementing management systems and procurement practices to carry out the purposes of ILS. It defined ILS as "a composite of the elements necessary to assure the effective and economical support of a system or equipment at all levels of maintenance for its programmed life cycle." [Ref. 2] This definition has been expanded, interpreted and refined in many ways since its issuance. Possibly one of the most relevant graphic portrayals of its intent is shown in Figure 3-6 in terms of "system worth."

This illustration is designed to portray the dual impacts of the elements of ILS on operational availability and logistics costs. If system effectiveness is viewed as the combination of performance capability plus operational availability, then it becomes apparent that emphasis on operational

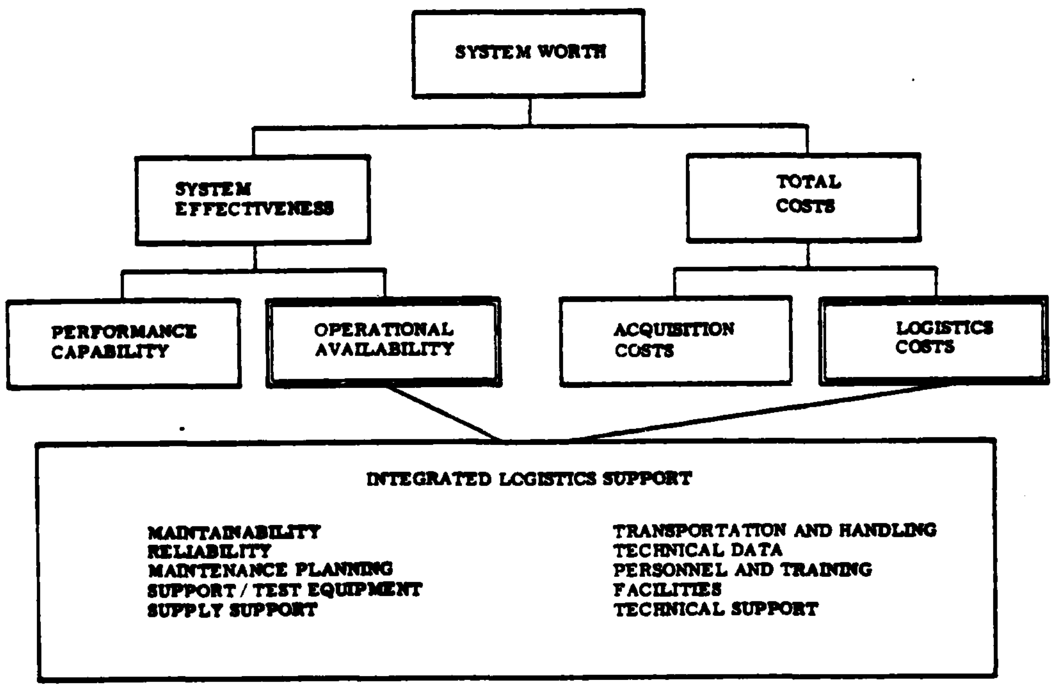


FIGURE 3-6: THE ELEMENTS OF SYSTEM WORTH [Ref. 6]

availability is essential to system effectiveness. The point made by users is that the tendency has all too often been to concentrate so heavily on designing for performance capability, that operational availability requirements of equal necessity are given little consideration. The frequent result in such cases is that logistics support, attempted in the manner of an after-thought subsequent to performance design baseline development, becomes a costly and time-consuming activity which may never wholly satisfy availability needs.

On the other side of the chart, logistics costs are combined with acquisition costs to indicate the total costs for the system or equipment. Logistics costs devour a major share of user funds. Much of these costs may be viewed as necessitated because of the failure to consider the ILS elements which go into operational availability during conception and throughout all subsequent phases in the procurement cycle. The objective of ILS, then, is to reduce logistics costs and increase operational availability by integrating logistics requirements into total system requirements at the earliest possible time and to consider logistics needs continually throughout the systems program.

The injection of logistics requirements into the procurement cycle in such a manner is expressed by DoD Directive 4100.35 in the first paragraph under "General Policies" as follows:

> Development of Integrated Logistics Support for a new system or equipment shall be initiated concurrently with the performance requirements or at the earliest possible time in the conceptual phase and at the procurement planning phase for commercially available items. The evolution of logistics support, that is, the integration of its elements shall be the result of progressive system analyses of the plan for use and the plan for support and the indicated tradeoffs between these plans through all phases of the project. [Ref. 2]

In viewing ILS as a management technique for reducing logistics costs, it should be remembered that the bulk of the costs for logistics efforts are incurred in the user's environment; i.e., such costs are in the form of military and civil service payrolls and in government owned and operated facilities. Under the ILS concept, the user and the producer have a mutuality of interest in reducing logistics costs since such action can be of financial benefit to both. By doing a better job of planning and designing the system during the acquisition phase, support costs could be reduced to the degree that would more than pay for increased acquisition costs. This concept is supported in DoD Directive 4100.35 which states that "the cost of developing Integrated Logistics Support shall be recognized as inherent in the overall cost for delivery of an operationally effective system or equipment." [Ref. 2]

The reduction of support costs can also have significant benefits for system flexibility since less support cost translates into less personnel, support equipment, facilities and spare parts requirements. This should mean greater

mobility of forces and improved ease of operation and maintenance. Furthermore, from the producer's point of view, an increase in funding for acquisition of systems and equipment means a potential for improved profit. Such profit would be in the form of an increased use of systems engineering and technical management processes to improve operational availability and reduced logistics activities in the user's environment. In summary, the ILS concept presents significant areas for achievement in improved system/equipment total performance and user/producer financial benefits.

2. Implementation of ILS

Shortly after publication of DoD 4100.35, the DoD Equipment Maintenance and Readiness Council established an ad hoc committee, with both military and industrial representation, to explore means for the implementation of the directive, including the development of methodology and tools. Nine tasks were pursued by nine subcommittees for about a year. The recommendations of the ad hoc committee resulted in the establishment of a DoD ILS Working Group. With the assistance of the Logistics Management Institute, members of this working group, representing all of the military services, prepared and issued a coordination draft of an ILS Planning Guide in October 1968 as DoD Directive 4100.35G. This document further clarified the elements of ILS and established typical actions to be taken in a time-sequence oriented block

diagramming system. Revision of the list of logistic elements includes:

a. Maintainability and Reliability

b. Maintenance Planning

c. Support and Test Equipment

d. Supply Support

e. Transportation and Handling

f. Technical Data

g. Facilities

h. Personnel and Training

i. Funding

j. Management Data

In October 1970, DoD Directive 4100.35 was reissued to reflect lessons learned from experience with the previous documents as well as improvements to the systems acquisition process. It stressed as a policy the use of a systems approach for "planning, analyzing, designing and managing the incorporation of logistic support into the acquisition systems," [Ref. 3] starting with the conceptual phase. Again in January 1980, this document was superseded by DoD Directive 5000.39 to bring it in line with the latest version of DoD Directive 5000.1 on Major System Acquisition. This latest revision again changed the list of ILS elements, representing the fourth change since 1964, to reflect a better balance between system design and logistics support. The latest revision includes:

a. The Maintenance Plan

b. Manpower and Personnel

c. Supply Support (including initial provisioning)

d. Support and Test Equipment

e. Training and Training Devices

f. Technical Data

g. Computer Resource Support

h. Packing, Handling, Storage and Transportation

i. Facilities

3. <u>The Role of ILS</u>

The requirement for carefully developed ILS programs for users and producers alike stems from the basic nature of logistics support activities. First, adequate lead time is necessary to provide for timely, economical and effective logistics support. Second, logistics support programs are influenced heavily by qualitative factors which tend to limit precise determination of requirements. Third, the separate elements of logistics requirements are interdependent and changes in one element must be evaluated against impacts on the remaining elements.

To provide the lead time, planning for support must start as early as the conceptual phase and continue through all follow-on phases. To control the qualitative influences on logistics support and ensure that predicted quantitative factors are realized, continuing adjustments of logistics requirements throughout test and development phases are

necessary. For the optimum cost-effective definition of support requirements, full integration of logistics is essential. Compositely, the three cited characteristics of logistics support call for management excellence over the life cycle of a system or equipment.

Although ILS is primarily pictured as a management and planning process, it is also a strong System Design activity. It is thus necessary to have a logically structured management process and its logically structured counterpart in systems engineering. To do this, ILS focuses attention on the logistics engineer and logistician and their roles in the system life cycle and the system acquisition process.

The logistician is a person representing the customer or user and his point of view. He is concerned with the operation of the logistic support system and therefore in the determination of logistics support requirements. The logistics engineer represents the producer or the design viewpoint. He is concerned with how the logistic support requirements can be implemented as part of prime and support system design to meet the needs of the logistician. Of importance to both the logistician and the logistics engineer is the cost-effective tradeoff between the design and operational elements of ILS, determined by the analytical technique of Logistic Support Analysis (LSA) which quantitatively links related design parameters and ILS requirements to system readiness objectives,

and which defines detailed support element requirements. [Ref. 8] In accordance with MIL-STD 1388 and DoD Directive 5000.39, LSA shall:

> ...include use of appropriate analytical tools and models throughout the acquisition cycle to evaluate alternative support concepts, to perform tradeoffs between system design and ILS elements, and to perform tradeoffs among elements in order to meet system readiness objectives at minimum cost. LSA shall be used to effect integration of support planning and design and consistency among ILS elements. LSA shall commence at Milestone 0 and be performed in increasing depth throughout the acquisition phases. [Ref. 4]

A more in-depth description of the systems design and support processes is presented in Appendix B, "Logistics Design Considerations," and in Appendix C, "Logistics Support Considerations."

IV. DISCUSSION

A. GENERAL

The technological triumphs in the IC world keep multiplying at a relentless rate, surpassing both performance and timing goals established in the early days of the VHSIC Program. Westinghouse has, for example, already fabricated for Control Data Corporation a special signal processor that not only incorporates the 1.25 micron feature size, but also contains 25,000 gates on a 120 X 240-mil size chip whose density figure of merit is more than 10 times better than the Phase 1 goals. Additionally, TRW/Sperry Univac estimates

that it could provide a VHSIC replacement for the Navy/Control Data Corporation AYK-14 computer, used in the McDonnel Douglas F/A-18, that would occupy only one-fifth the volume, weigh only one quarter as much, operate at more than seven times the speed of the existing XN-5A version of the AYK-14 machine, and consume 80% less power. Indeed, there are many more equally remarkable success stories just like these.

Such notable achievements in these accelerated developments are finding an unexpectedly large and unusually welcomed counterpart in the form of reductions in chip manufacturing costs. Although it is not across the board as yet, dramatic progress has been demonstrated in both mass produced and custom designed chips. As recently as March 1981, for example, the price for a mass produced 64K RAM (Random Access Memory) chip was $28. Today the price is down to $8 and next year the price may drop as low as $6 or even $4. Likewise, companies like the Boeing Aerospace Company have been able to perfect the technique of CAD for custom made chips so as to reduce the time and cost requirements from 6-12 months and $20K each to approximately 6 weeks and $.5-1K per chip, as Figure 4-1 illustrates, by incorporating 20 to 40 designs into the production of one wafer.

Recognizing then this intense drive for previously undreamed of performance levels occurring in juxtaposition with a correspondingly significant reduction in production costs,

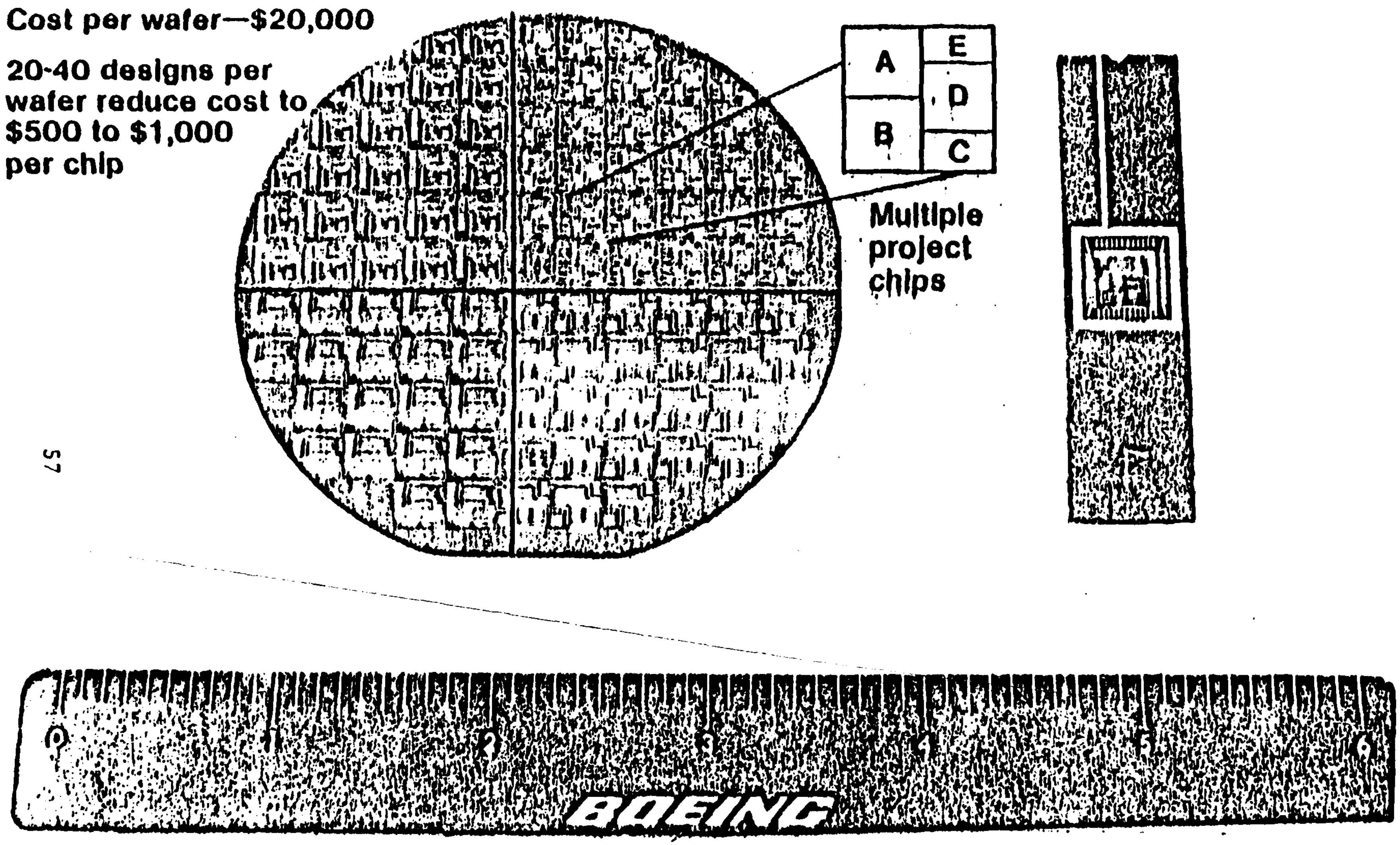


FIGURE 4-1: THE USE OF MULTIPLE PROJECT CHIPS TO REDUCE PRODUCTION COSTS
(Courtesy of Boeing Aerospace Company)

what implications are there for implementing VHSIC technology within the framework of the conventional ILS approach set forth in Chapter III? Both theoretically sound and legally bound by DoD directives, acquisition programs for systems and equipments shall have an ILS program structured to meet program readiness objectives within established cost, schedule, performance and logistics constraints, beginning at Milestone 0. Given this mandate, therefore, can a weapon system manager properly balance operational and support systems requirements? Will the inherent nature of the VHSIC technology help or hinder this process? What are some of the perceived pitfalls in the execution of such a program?

B. IMPACT ON LOGISTICS SUPPORT

GAO has indicated that one of the most prominent detractors from the effectiveness of deployed systems was logistics support. Even though DoD is now placing greater emphasis on this area during the acquisition process, including the adoption of a policy that supportability is as important a consideration as cost, schedule and performance, this policy may never completely materialize because of the following reasons:

1. The process for interfacing logistic considerations with other design considerations (i.e., LSA) is very difficult to do, as data needed for design decisions are difficult to obtain and there is a shortage of trained people to do the analysis.

2. Quantitative analysis needed to assess logistic plans and support related parameters for meeting system readiness goals may be very difficult to perform because the analytical models for making such assessments may not be adequate.

3. There is generally little incentive for management to invest development funds or to tradeoff technical performance to improve supportability of a system because it is very difficult to quantify the benefits of such investments and tradeoffs. As a consequence, most design tradeoffs may continue to favor cost, schedule and technical performance. [Ref. 1]

The implementation of VHSIC technology will, nonetheless, significantly reduce the "gray" areas that impair the exploitation of supportability considerations. For example, the weight, power, size and reliability factors associated with highly integrated circuits have far reaching cost and effectiveness implications for LSA. As design technology approaches a systems-on-a-chip capability, the availability problems of complex electronic systems will dramatically decline because large scale integration circuits contain proportionately fewer external interconnections--the major source of reliability degradation and systems failure. For example, the TRW/Sperry Univac team projected a 10-fold increase in the mean-time-between-failure (MTBF) for their replacement computer cited earlier in this chapter. Additional chip area

will therefore be available for implementing self-repair and BIT that will further increase reliability and reduce maintenance. Increased reliability and decreased cost will furthermore impact the maintenance plan and logistic support models which consider repair/discard, provisioning, inventory and manning considerations. The OPUS model described in paragraph 10.4.4.2 of Appendix C would be an appropriate analysis tool in this context. Such a model has the capability of conducting a cost-effectiveness evaluation of alternative maintenance and support concepts for alternative system configurations, or even determining logistic design considerations for a specified fixed cost level of effort.

In short, the advantages of system reliability improvements for Phase 1 specifications allow for a 10:1 increase in chip complexity for a device that consumes only one sixteenth as much power as a currently available 5-micron device. In addition, they also provide more quantifiable factors to evaluate design considerations, assess logistics planning and perform support analysis. Considering the financial incentives associated with the VHSIC Program and forecasted for this technology in general, there is a unique opportunity to emphasize at an earlier time the supportability aspects as much as the performance characteristics (see Figure 4-2). Such action is particularly germane since the trend toward more maintenance-free systems is not only desired, but demanded by the operational functions that these systems will perform.

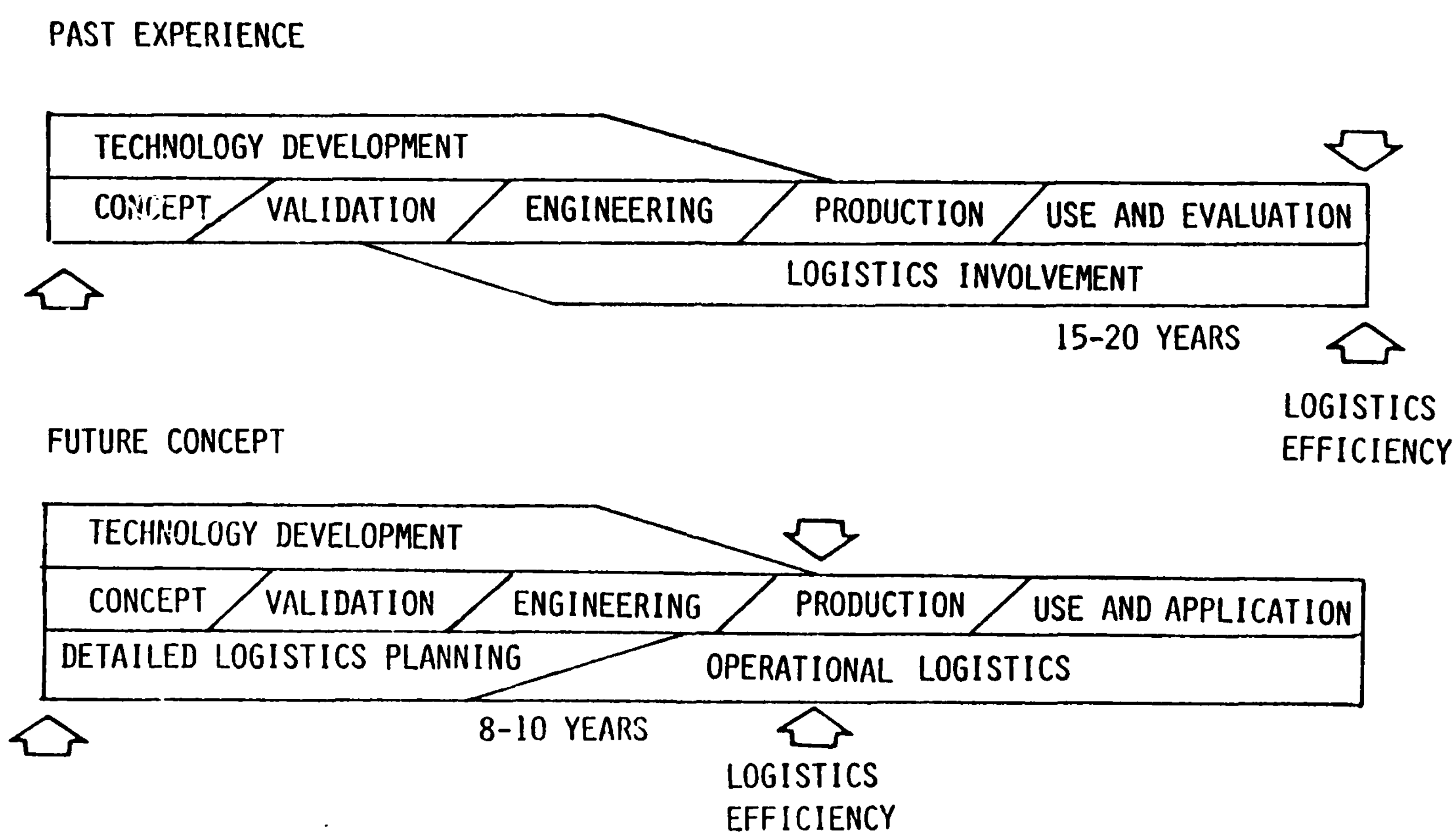


FIGURE 4-2: LOGISTICS LEADTIME OVER THE PRODUCT LIFE CYCLE

(Courtesy of Boeing Aerospace Company)

Disadvantages do exist, however, and must be researched and evaluated against readiness goals or political policies. One such disadvantage is that the resistance of interconnections in this reduced-scale configuration increases as the second power of the scale factor, resulting in an increase in current density proportional to the scale factor. This can result in metal migration and other adverse effects on reliability. Another disadvantage is the vulnerability to radiation which may come from nuclear blast, earth radiation belts or space radiation, resulting in potential ionization, a transient effect in which electrons are temporarily removed from their atomic orbits, or even displacement, a permanently damaging effect where an atom is removed from its lattice site in a crystalline solid to an interstitial position, leaving a vacancy. All of these effects jeopardize system reliability and must be researched further.

C. IMPACT ON HUMAN FACTORS

The influence of human factors was another one of the most prominent detractors from the effectiveness of deployed systems, according to GAO, who recommended that DoD modify human factor specifications, standards and handbooks to cover adequately limitations that can result in human induced system failures. In addition, DoD was asked not only to develop common methodologies and data sources for use by system designers in forecasting skill levels of military

personnel from 5-10 years into the future, but also to consider human factors in system developmental stages. Since evidence of weapons systems failures due to human ineptitude or poor human reliability may be as much as 50% of all weapons syste failures, GAO warned that:

> Military specifications, standards and handbooks on human factors do not adequately consider human limitations such as skill levels, proficiency, availability, environmental stress and fatigue...The problem of human-induced failures may very well become worse...Attendant to the increasingly complicated nature of systems are the lower educational and aptitude levels of personnel now entering the services, the shortages and high turnover rate of experienced personnel, which leads to very low overall experience levels, and the effect of greater use of complex and sophisticated automatic checkout and built-in test equipment. [Ref. 1]

VHSIC is appropriately germane to this element of discussion, in that its ultimate goal will be to create an interface with maintenance personnel which demands less skill to restore a failed system to operational status. Resident in the VHSIC chip itself will be the technology to effect self-repair through circuit redundancy, to allow for BIT, and to maintain reference information such as configuration, parts list, maintenance check-off list, organizational level instructions, and/or maintenance history. In addition, the technology can be resident in the support equipment to provide maintenance aids, data management, training development and task simulation. The net result of employing "smart systems" with built-in artificial intelligence will be to reduce maintenance and training time, reduce support personnel requirements, reduce maintenance proficiency requirements and

thereby reduce maintenance errors. Coupled with the LSA achieved through such support models as OPUS cited in the previous section, entire level(s) of maintenance could foreseeably be reduced or eliminated incident to the effect VHSIC would have on maintainability, testability, repairability, reliability and supportability.

D. IMPACT ON INDUSTRIAL INVOLVEMENT

It becomes readily apparent to even the casual observer that the goal of VHSIC is genuinely compatible with the goal of ILS. Both seek to maximize performance, commonality and reliability while minimizing test, maintenance and other support requirements.

The degree of success achieved is evaluated when a newly developed system or equipment is turned over to the fleet for service. This is a determination of whether the system, after undergoing appropriate test and evaluation under actual operating conditions, is considered to meet the prescribed operational requirements for both performance and supportability. Success is a reflection of how well the user-producer dialogue/interface was maintained between the logistician and the logistics engineer.

Although the dialogue appears to progress sequentially through the Planning, Acquisition and Use Periods, in reality there are many feedback paths in which the results of later phase activities require going back to previous phases. There

appear to be two major feedback paths in the life cycle of a system, one primarily producer-generated and the other primarily user-generated, as shown in Figure 4-3. The first one, called "systems engineering feedback," is concerned with the Planning and Acquisition Periods, when the outputs of one phase indicate that operational or system requirements cannot be met as stated, or can only be achieved with significant risk, resulting in project termination or redesign.

The second feedback path, called "operations and support feedback," results from data received when the system is put back into operation in the field environment and its actual cost-effectiveness is determined. Design deficiencies, production quality assurance problems, unanticipated environmental changes, etc., are treated here in this second feedback loop. The need for strong, continuing user-producer communication throughout the system's life cycle is critical. If this dialogue breaks down at any point before the system is replaced or retired, insurmountable support problems could occur.

The current concern over diminishing military sources (DMS) for procurement of existing hardware or spares is an excellent example where the operations and support feedback path has broken down. This results from the obsolescence or discarding of a production technology without any warning to the user until it is ready to be executed, causing unprogrammed emergency life-of-type buys. Presumably, if a continuing

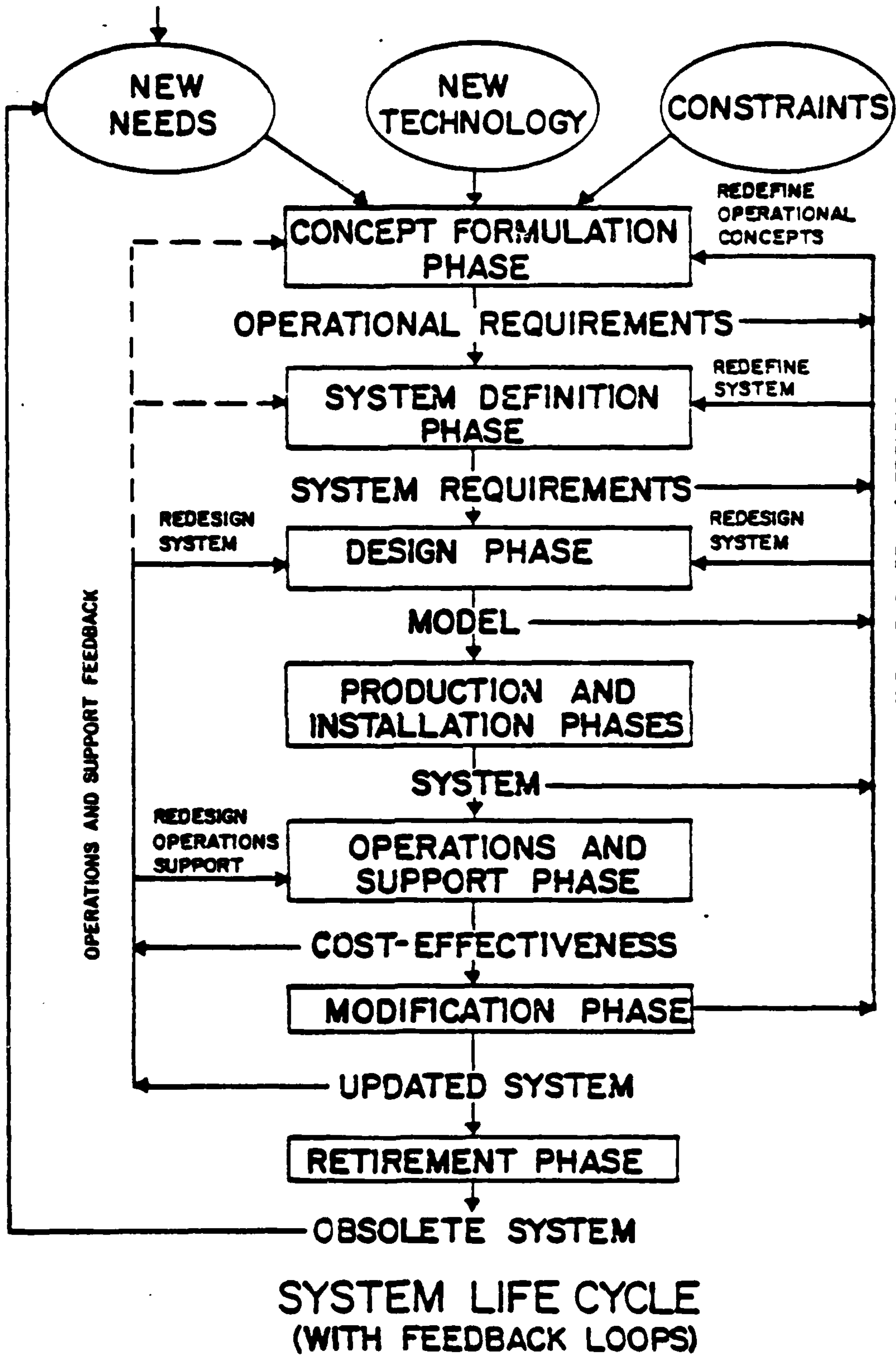


FIGURE 4-3: THE SYSTEM LIFE CYCLE WITH FEEDBACK LOOPS [Ref. 8]

user-producer dialogue were maintained, sufficient planning for a redesign could be accomplished via a normal feedback loop. Only with VHSIC technological achievements can avionics equipment now be salvaged from this crisis management scenario, wherein the newly-acquired capability to produce customer-designed chips in a cost-effective manner can be initiated. As whole technologies assume shorter life cycles of their own, it becomes even more imperative that the user-producer dialogue be protected and nourished.

This is perhaps the intent of GAO's third and final element found to be prominently detracting from the effectiveness of deployed systems, that being the need for quality assurance. The responsibility herein lies with both the producer and the user to incorporate into the acquisition process at the earliest possible time a dialogue which addresses and incorporates both the operational and support system factors over the SLC. This would include the means to establish and maintain in-service data collection systems to report the measured values of parameters that relate to readiness, maintenance manpower and logistics support elements and costs.

It would, for example, track and illustrate how and where the achieved versus predicted MTBF is divergent because experience has shown that predicted MTBF can be as high as 6-times greater than actual MTBF, as demonstrated in Figure 4-4. It would also help pinpoint deficiencies where large numbers

ACHIEVED $MTBF_A$	PREDICTED $MTBF_P$	WUC	AIRCRAFT TYPE	NOMENCLATURE
129	750	72GA	C-5A	Altimeter
17.8	17.1	73A	A-7D	AN/APQ-126
27	184	73JC	FB-111A	AN/APQ-114
31	250	73KB	FB-111F	AN/APN-146
12.3	300	73D	FB-111A	AN/APQ-110
116	258	73P	F-111D	AN/APQ-153
137	184	73VA	F-111	AN/APQ-113
44.1	328	722B	P-3C	Radar Altimeter
223	1000	723A	P-3C	AN/APN-187
28.6	110	726A	P-3C	AN/APS-115
324	1500	722B	A-6E	AN/APQ-194
18.3	106	73A1	A-7C	AN/APQ-126
61.5	500	73A3	A-7C	AN/APN-190

FIGURE 4-4: PREDICTED VS ACTUAL MEAN TIME BETWEEN FAILURE FOR RADAR SYSTEMS

(Courtesy of Boeing Aerospace Company)

of removed components check as serviceable, what percentage of the time units flow to the depot, etc., all of which have direct consequences on training, diagnostics, and test and checkout assessment. Such a data base would afford timely trend analysis and feedback to both user and producer for appropriate corrective action.

V. CONCLUSIONS AND RECOMMENDATIONS

A. GENERAL

As a result of improvements in fabrication technology, large scale integrated electronic circuitry has become so dense that a single silicon chip may contain tens of thousands of transistors. Many of these chips, such as microprocessors, now consist of multiple complex subsystems, and thus are really integrated systems rather than integrated circuits. Still the key to the entire process is the capability to integrate a number of circuits to perform a specified function at a given performance level.

Even more astounding is the fact that current achievements are only the beginning. Achievable circuit density now doubles with each passing year or two. Physical principles indicate that transistors can be scaled down to less than 1/100th of their present area and still function as the sort of switching element with which digital systems can be built. By the late 1980's, it will be possible to fabricate chips

containing millions of transistors. The devices and interconnections in such very large scale integrated systems will have linear dimensions smaller than the wavelength of light, approaching what is being termed as systems-on-a-chip technology and providing complex designs for higher processing speeds to perform peculiar military functions.

Such achievements in microelectronics present a challenge, not only to those involved in the development of fabrication technology, and not only to the system designers and computer architects involved in the design process, but also to the logisticians and logistics engineers concerned with the operation of the logistic support system and its interface with the system life cycle and system acquisition process. Until recently the design of integrated circuitry has been the province of circuit and logic designers working with semiconductor firms; but now that the performance potential is being realized in response to such impetus as the DoD's VHSIC Program, it is becoming imperative that systems design be a concern of the hardware designers/manufacturers as well as those active in the acquisition and support of those systems.

In the first case, most observers agree that one of the most beneficial effects of the DoD VHSIC Program has been to force semiconductor specialists and system designers to interact jointly to exploit advances in microelectronics and to seek innovative microcircuit architectures that can be used in a large number of weapon systems. This will significantly

help to satisfy one of the basic VHSIC objectives of finding a moderate number of very complex-function microcircuits that can find widespread use in many different applications. This is necessary to create a sufficient market to ensure that at least two commercial sources will be available and that all defense system manufacturers, including smaller companies, will have access to the devices.

The second case focuses on the utilization of the ILS concept which, as part of all other aspects of system acquisition and operation, is concerned with the definition, optimization and integration achieved by systematic planning, implementation and management of logistics support resources throughout the system life cycle. This concept is realized through the proper integration of logistics support elements with each other and through the application of logistics considerations to the decisions made on the design of the hardware system and equipment as a part of the systems engineering process. As with the concept of the integrated circuit, the key to the entire process is the capability to integrate a number of elements to perform a specified function at a given performance level, including

1. The Maintenance Plan
2. Support and Test Equipment
3. Supply Support
4. Transportation and Handling
5. Technical Data

6. Facilities
7. Personnel and Training
8. Logistic Support Resource Funds
9. Logistic Support Management Information

The ILS function will therefore provide recommended support parameters for the above elements. Such parameters will be provided as qualitative and quantitative reliability and maintainability inputs to the design process for use in design tradeoffs, risk analyses and development of a logistic support capability responsive to the operational requirements of weapons systems.

B. CONCLUSION

The VHSIC Program therefore has a unique opportunity to gain, on the one hand, a significant amount from utilizing the ILS process and to contribute, on the other hand, an equally important amount to that same process. Recognizing that the technological advances afforded by VHSIC can be resident in the system hardware as well as resident in the support elements themselves, an unparalleled synergistic effect could conceivably be achieved.

Logistics considerations for VHSIC components must, in summary, be viewed as the composite of all considerations necessary to assure the effective and economical support of a system throughout its programmed life cycle. It is an integral part of all aspects of system definition, design,

development, test and evaluation, production and/or construction, and operational use. In other words, the prime equipment and the elements of logistics support must be developed on an integrated basis to produce a cost-effective product.

Logistics support must be initially planned and developed as part of the overall system development process to assure an optimum balance between the prime equipment and its related support. This balance considers the performance characteristics of the system, the input resources required and the evaluation of the results in terms of effectiveness and cost. In areas where alternate design approaches are considered, each alternative must be evaluated on the basis of the cost effectiveness of the prime equipment and its applicable support, thus leading to the selection of an overall preferred system configuration. The prime equipment design influences logistics support requirements and these support requirements, in turn, impact the overall effectiveness and efficiency of the total system. The result is an iterative process that refines the output until an optimum balance is obtained. The objective is to provide the optimum level of support at the proper location and at the right time. Providing the required elements of support either too early or too late is costly.

Once planning is completed and logistics has been properly addressed in the development process, the specific elements of support identified through analyses are provisioned,

produced or directly procured, and verified through compatibility testing with the prime equipment. As a result of this verification, problem areas are readily identified and corrective action is accordingly initiated. The applicable items of logistics are then delivered for operational use and support of the prime equipment in the field throughout the system life cycle.

C. RECOMMENDATIONS

The potential long range contribution of VHSIC technology to military applications is beginning to take shape. Achievements already demonstrated in the DoD VHSIC Program underscore the fact that:

> ...increased maintenance and decreased reliability are not inherent in complexity. Integrated circuits have proven this. As the capability built into a given silicon chip has increased from one transistor to 100 thousand transistors, the reliability of the chip has remained roughly constant. In the end, if a system can be built onto a single chip, it can be extremely reliable. [Ref. 9]

Maximum performance and reliability are not, however, the only goal of the VHSIC Program. It also seeks to minimize test, maintenance and other support requirements by creating an interface with maintenance personnel that demands less skill to restore a failed system to operational status. Although this aspect has yet to be fully incorporated, it has available currently revised directives for including support considerations in the systems development and acquisition process. Such guidance ensures that the ILS approach is integral to all weapons systems management.

This thesis has furnished the current status and points of comparison of the DoD VHSIC Program and ILS approach to weapons systems management. In an attempt to prevent the VHSIC technology transfer process from adding to the GAO's growing list of complaints about new, high technology oriented systems, the following recommendations are submitted for consideration by weapons systems and project managers who may be introducing VHSIC technology into weapon system design or redesign. It is intended that these recommendations will help exploit VHSIC technology developments to the fullest so that balanced operational and support considerations will contribute to increased readiness and operational capabilities of our military forces. It is therefore recommended that weapons systems and project managers:

1. Incorporate ILS planning at the earliest possible time in the conception of VHSIC system design. Adequate safeguards should thereafter be exercised to protect ILS funding for all ILS elements and preclude the siphoning off of funds for development of systems or procurement of installed equipment. As is so often the case, the importance of a balance between operation and support considerations is recognized, but not controlled, thereby allowing for early redistribution of funds and building in major support problems from the very beginning of a system's life cycle.

2. Maintain the user-producer dialogue throughout the product life cycle to ensure continuity for both operation

and support requirements. Fabrication technology for integrated circuits is very volatile, developing so fast that there exists the risk that industrial suppliers may abandon technology processes well before the end of a product's life cycle. An active dialogue would ensure that both users and producers would be cognizant of technological developments. Adequate safeguards could be implemented for protecting tapes for IC fabrication and for ensuring that procurement sources exist. This might include government ownership of fabrication tapes and/or foundry facilities at major rework/overhaul sites to provide for surge requirements or protect against technology obsolesence.

3. Accelerate the VHSIC technology insertion process to include those avionics systems now facing serious support problems, either incident to DMS or to recurring reliability degradation. Custom designed chips are becoming comparatively inexpensive and available well within routine procurement leadtimes. Timely action could possibly reduce or eliminate costly and unprogrammed life-of-type procurements, as well as preclude unnecessary inventory increases.

4. Accelerate the VHSIC technology insertion process for support systems including maintenance aids, intelligent support equipment, training devices, simulators, and data management. The performance and reliability improvements in prime equipment can also be realized in these areas. Such benefits as high density, low cost, high reliability and high

throughput rates would greatly enhance the support effort. Increases in efficiency and decreases in personnel and high maintenance efforts would multiply the cost-benefits achieved through the implementation of VHSIC technology.

5. Analyze the impact of VHSIC technology on all ILS elements. The implications of having VHSIC chips installed in both prime equipment and support systems yield both major and consequential changes in the conventional approach to systems management. If actual MTBF begins to approach the predicted MTBF for VHSIC components, for example, the Maintenance Plan could require dramatic changes in the conventional three levels of maintenance structure and in the source, maintenance and recoverability (SM&R) philosophy. Improvements in Personnel and Training requirements, Facilities, as well as Technical Data management would impact such areas as provisioning, spares for allowances and wholesale inventory, entry level skills and repair turnaround time. In short, the whole process of material and personnel management would require review in order to obtain the maximum benefits from the systems engineering process.

6. Accelerate research for composite materials which will ensure that VHSIC components are tolerant to temperature and immune to radiation hazards germane to wartime environments. Efforts to improve equipment survivability and reduce vulnerability must be dedicated now before the large proliferation of VHSIC components takes place. Such accomplishments

are imperative to the overall long range success of the DoD VHSIC Program.

7. Support and expand the DoD VHSIC Program to guarantee a competitive edge for the military forces. The relationship between military requirements and industrial willingness must be cultivated in terms of contracting improvements and financial incentives. Performance improvements and product life cycle cost savings must be measured and reported to further stimulate program growth and strive for maintenance-free electronics and system-on-a-chip technology. Users must be educated on the changes in maintenance philosophy and supply support, from operating computer-aided support equipment to understanding the significant reduction in piece-part inventories. Feedback must be channelled back to designers to ensure standardization of terminology and hardware, to check interoperability with other VHSIC and non-VHSIC systems, and to maintain data collection and information systems for cost and trend analysis.

D. TOPICS FOR FUTURE RESEARCH

Additional research in the following areas is recommended:

1. Conduct logistic support analysis for one or more of the Phase 1 VHSIC systems to ascertain ILS cost savings over a 20 year life cycle. This could conceivably be done with the METRIC or OPUS support models and set up to evaluate life cycle cost elements, reliability improvements and design-to-cost approaches.

2. Examine the impact of VHSIC technology upon the elements of ILS. This would include such areas as examination of the conventional three levels of maintenance; an evaluation of how and where VHSIC could best be incorporated into support equipment; and what effect VHSIC would have on the design/support factors of maintainability, testability, repairability, reliability and supportability.

3. Determine how and where the DoD VHSIC Program should go from its present status. Such an assessment would include an evaluation of where competing countries like the Soviet Union stand in technological accomplishments; what controls should be placed on technology exports or implemented to preclude theft or leakage of information; and what steps should be taken to address technology continuity, industrial responsibilities or involvement, as well as mobilization and surge potential.

APPENDIX A

VHSIC AND DEFENSE TECHNOLOGY[1]

by

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1980

DoD is investing $225 million in its Very High Speed Integrated Circuit (VHSIC) Program over a six year period that began in 1979 [Ref. 1]. VHSIC will develop advanced militarized integrated circuits for application in future military systems in a timely and affordable manner. It is appropriate here to reexamine the VHSIC Program and its objectives in view of the present concerns regarding the readiness of U.S. military hardware. These concerns focus directly on defense policy issues. Present U.S. defense policy relies upon qualitative superiority of weapons systems to compensate for numerical inferiority. VHSIC is a high technology program and its products can provide a new level of performance and reliability; it is important to note that the readiness and hence, operational capabilities of our military forces can also be improved by exploiting VHSIC technology developments. This paper describes the VHSIC Program, examines the critical policy issues, and provides examples of future VHSIC applications. It argues that VHSIC will serve our military forces well--if reliability and maintainability are built into our electronic systems, if greater emphasis is placed on the operational requirements of system application, and if a proper balance between performance and life cycle cost is maintained.

VHSIC Background

In the 1950's it became obvious to DoD that despite the introduction of transistors, failures in electronic equipment were still threatening the success of military operations. At the same time, the cost of support functions--supply, maintenance, and repair--were increasing rapidly. A new approach to electronic components was needed which would offer improvements in reliability, size and weight

[1]All references cited herein are separately identified at the end of this appendix.

reduction, reduced costs, and at least equivalent performance. In 1958, in response to this need, the Air Force selected an approach, termed molecular electronics. The concept was the synthesis of complete electronic circuits on blocks of semiconductor materials. This concept is credited with stimulating J. S. Kilby, of Texas Instruments, to invent the integrated circuit in 1958 [Ref. 2].

The integrated circuit era was launched in 1959 by DoD's award of large development contracts to Westinghouse and Texas Instruments, followed in one year by a production contract at Texas Instruments. Demonstration computers built with the first integrated circuits generated much interest. In 1961 Fairchild, without government support, developed its first circuits. Between 1961 and 1964 a broad range of technological advances were made and integrated circuits became broadly available. In 1962 Autonetics proposed to the Air Force the application of integrated circuits to reduce the weight of the guidance package in the Minuteman missile. Adoption of this proposal was followed in two years by a successful flight test of the integrated circuit guidance computer. This rapid application of integrated circuits demonstrated to industry that integrated circuits were essential in future electronic system designs. Soon major efforts were underway in the Apollo and submarine-launched-ballistic-missile programs, and in a variety of civilian applications. From a market of $4M in 1962, sales increased to about $50M in 1965, climbing to $1B by the early Seventies. By 1970, all digital electronic systems and a majority of low-power analog electronics were using integrated circuits [Ref. 3].

In the early 60's, bipolar planar circuits with several gates per circuit were common. By the end of that decade, the surface field effect or MOS transistor technology was in use and large scale integration in the form of the 4-bit microprocessor was introduced in 1971. Gate densities were approaching 100 gates/mm^2 and "very large scale integration" (VLSI) efforts were underway.

Following its major role in supporting the integrated circuits (IC's) industry in the early 1960's, the DoD began to deemphasize support of this technology in the 1970's. DoD planners were convinced that industry would pursue technology developments without major DoD support. This expectation turned out to be correct far beyond the projections of the original analysis. Encouraged by a rapidly growing commercial market, integrated circuit technology has expanded exponentially over the last 20 years. During the same time period [illegible]nal share of the market commanded by the DoD dropped [illegible] in 1965 to about 7% at the close of the 70's.

These events have had a substantial impact on the utilization of current integrated circuit technology by the DoD. Significant differences exist between DoD requirements and commercial requirements for IC's. Although many commercial applications involve somewhat hostile environments, mostly mechanical and thermal stress, none are as severe as those that characterize military mission scenarios. Although many commercial applications put stress on reliability, as in vehicle and equipment control, the DoD demands are more stringent. Many commercial applications require that circuits be tested and faults be diagnosed, but DoD applications stress this requirement more severely. Further, the need for operation in maintenance-free environments will become increasingly more important in the future. Thus, commercial IC's fall short of DoD requirements largely in terms of reliability, testability, immunity to environmental stress, and speed. As a result, IC's for DoD systems need either to be selected (assuming they already exist) and extensively tested; to be custom designed, fabricated and tested; or both. This leads to higher cost but also, and more significantly, to a lag of several years between the availability of a commercial circuit and the availability of its military counterpart. With IC technology advancing rapidly, this means that military IC's are substantially behind the commercial state-of-the-art in processing capability [Ref. 4].

This situation developed gradually and, although the results are significant, they probably would not have been sufficient to motivate a major DoD initiative. However, a more alarming development occurred. There is evidence that the U.S. lead in military IC technology, a lead which was substantial, has been significantly eroded. Intelligence reports in October 1977 indicated that the capability of the Soviet Union to fabricate and deploy advanced military IC's exceeded our predictions. This resulted in an initial need for reexamination of integrated circuits by DoD. This review showed that U.S. military IC needs had not received appropriate emphasis because of the strong commercial demand. It was found that the application of LSI in military systems had not been extensive and that the advantages offered in terms of improved signal and data processing capabilities, reduced life-cycle costs, and greatly reduced size, weight, and power had not been exploited. It was further recognized that, as gate densities extend into the VLSI range, these advantages will become even more valuable and will initiate a new era in electronics, termed by many as "system-on-a-chip." This concept has profound implications for the DoD with respect to systems architecture, fault-tolerant operation, and new mission capability. Based upon these points, a program to rectify the concerns was formulated in January 1978 [Ref. 5].

On 19 July 1978, the Under Secretary of Defense issued a memorandum to the three Service Assistant Secretaries for Research and Development that formally established a major new DoD initiative to develop a "new generation of very high speed IC's suitable for rapid deployment in military systems" [Ref. 6].

On 28 September 1978, a second memorandum provided further funding guidance and clarification. It also requested that each Service define at least two system demonstrations which would use developed VHSIC chips to provide for early technology insertion. As VHSIC planning proceeded, it became evident that the program needed strong "systems-pull" and, accordingly, system needs were examined carefully. But before VHSIC was contractually initiated, VHSIC management took under consideration Congressional program concerns which were outlined in the House Armed Services R&D Subcommittee 15 May 1979 Report which deferred to entire authorization for the VHSIC Program. This deferral was based on policy concerns relating to management structure and to the transfer of VHSIC-generated technology within the U.S. so as to maintain competition in the semiconductor industry. Congress was also seriously concerned about what measures would be taken to control the export of VHSIC technology. Throughout the summer of 1979, meetings were held with staff members of this Subcommittee as well as with the Senate R&D Subcommittee in an effort to resolve the Congressional concerns. In October 1979 the VHSIC Authorization Request was approved in Joint Conference. The VHSIC Program has been modified to be consistent with the Congressional guidance as follows: the International Traffic in Arms Regulations (ITAR's) have been imposed where applicable, a VHSIC Program Office has been established in OUSDRE to provide overall management authority and funding control, and all major contracts will contain a second-sourcing clause.

In June 1979 the first VHSIC Request for Proposals was issued and the initial awards were made in March 1980. On 26 February 1980, a third memorandum was issued that established the VHSIC Program as one to be executed by the three Military Departments but with overall management cognizance, including funding control, by OUSDRE. A complete management plan for VHSIC was approved in March 1980. A total of $225M is currently planned for the Program to be expended over a 6-year period.

Program Description

The VHSIC Program is organized conceptually into four phases: 0, I, II and III. Phases 0, I and II will be carried out consecutively whereas Phase III will be carried out in parallel with Phases 0, I and II. Figure A1-1 shows the anticipated time sequence of these phases. Phase 0 contracts were signed on 7 March 1980 and the program is planned to continue into 1986.

Each phase of the program has distinct goals, although there is considerable cross fertilization between phases. Phase III is designed to provide high technology support for submicron development; however, it is expected that early results from this phase will also benefit Phases Ia and IIb as well.

The overall objective of the VHSIC Program is to develop militarized, advanced capability IC's which will be introduced into future military systems in a timely and affordable manner. The expected benefits from this include advanced military systems capability, high return on investment, reduced life-cycle-costs, and an increase in our lead in military IC's by several years. The DoD expects VHSIC to leverage the large commercial R&D efforts of the American semiconductor industry so as to advance IC technology toward those objectives that are peculiar to military applications: increased computational speed and efficiency; reduced size, weight and power requirements; enhanced reliability, testability, and maintainability. DoD expects to achieve these advances directly in VHSIC militarized circuits with high reliability, ease of testability and diagnosis, and high tolerance to military stress environments.

Phase 0 was a study phase to define the detailed approach and the plans for achieving the ultimate objectives of the VHSIC Program. For example, innovative approaches, to achieving VHSIC goals in system partitioning and architecture and to achieve functional commonality were sought. The contractor analyses proceeded in a top-down fashion starting with the selection and analysis of at least three projected military systems or subsystems to determine their signal and data-processing requirements and to identify the broadly applicable VHSIC chips or modules required. This objective, as mentioned above, is to achieve commonality. The contractor is to define a set of VHSIC "building blocks" out of which a maximum of military high performance electronic systems could be constructed with a minimum of customization. It is not clear at this writing at what level of integration this modularization will occur. In a sense, a VHSIC chip will already be an integrated system and it is envisioned that many systems will consist of only a few chips. With such increasing levels of integration, there seems to be a strong trend toward customization as each chip becomes a system in itself. The microprocessor is probably the only example in which this has not been the case. However, microprocessors and microprocessor-based architectures are likely to be too slow for many VHSIC applications. In Phase 0, architectures and design approaches will be selected and investigated to implement VHSIC chips with 1.25 micrometer (Phase 1) and submicrometer (Phase II) minimum feature size devices.

A key aspect of the program is the requirement for the VHSIC coordinators to define and describe viable and effective

procedures for making VHSIC components available to all other DoD contractors and government laboratories in a timely and affordable manner. This concern is addressed in the VHSIC Statement of Work for Phase 0. There is also a special clause in the VHSIC Phase 0 contracts in which the contractor agrees "to license and assist government designated parties to use contract products for government purposes." This is to include the development of second sources and covers both hardware and software developed under the program. Finally, under the Phase 0 effort, plans are to be described for rapidly introducing VHSIC's into DoD systems.

The main intent of Phase 0 is to enable contractors to study and analyze the VHSIC Program requirements sufficiently to determine what problems are likely to be encountered and what approaches are likely to be the most successful. The contracts include the preparation of proposals for Phase I.

As indicated in Figure A1-1, Phase I is divided into two parallel efforts. Phase Ia is directed to the development of complete electronic brassboard subsystems within three years of the Phase I start. These brassboards may consist of several VHSIC chips including "building block" modules with a minimum clock rate of 25MHz and a functional-throughput-rate (FTR) of 5×10^{11} (clock rate times gate density). In Phase I, a pilot line production capability will be established for this technology. Minimum requirements of reliability, testability and environmental immunity will be demanded. Phase Ib consists of initial efforts to extend IC technology to submicrometer feature sizes and corresponding circuit complexities. These efforts include high resolution lithography and replication techniques, submicrometer device design and modeling, substrate improvements, epitaxial growth improvements, metallization reliability, interconnect analysis, appropriate CAD techniques, architecture and systems considerations. Chips resulting from this effort will be characterized by an FTR of 10^{13} gate-Hz/cm^2. A feature of both Phases Ia and Ib will be the development of built-in, on-chip, testing technology including design for testability. Specific requirements for reliability and testability will be developed in the Phase 0 efforts.

Phase II is similarly divided into two parallel programs--Phase IIa which will provide subsystem demonstrations based on Phase Ia brassboards, and Phase IIb which continues the Phase Ib submicrometer development effort. Phases Ib and IIb are directed at developing all aspects of IC technology necessary to cross the so-called one-micron barrier, which is considered by many to be the practical limit of conventional optical lithography and fabrication techniques. The end goal of these efforts is the development of a pilot production capability for such advanced chips. This includes not only

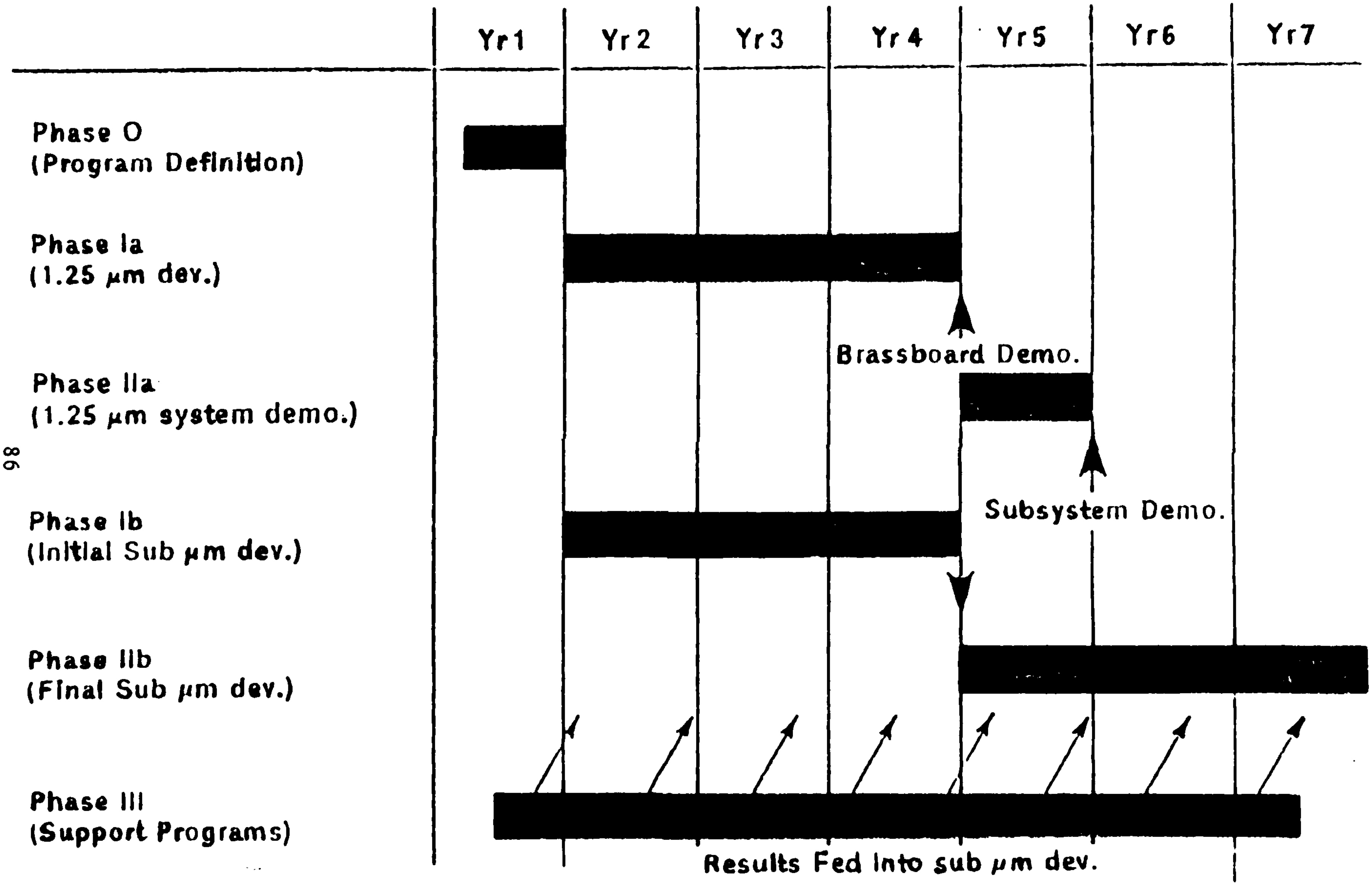

FIGURE A1-1: VHSIC PROGRAM SCHEDULE

lithography and fabrication but also design, architecture, software and testing technologies. Subsystem demonstrations of Phase IIb technology developments are expected at the end of the program or shortly thereafter through extensions or other Service funding.

Phase III, the VHSIC Support Program, runs in parallel with the main program efforts. Whereas the Phases I and II program contracts are expected to be large, vertically integrated efforts with each contractor covering all aspects of VHSIC development, Phase III will consist of many smaller shorter term efforts in key technology areas designed to feed into the main program. Part of the motivation for establishing VHSIC-III was to permit and encourage the participation of universities and small businesses in the program. It is expected that VHSIC-III may amount to as much as one-third of the total program, with the funding of this phase to be heaviest in the early years. VHSIC-III support programs are considered essential to the development of a solid technology base, to stimulate innovation and provide sources for specific design, manufacturing and test equipment. Efforts will focus on high resolution lithographic equipment and processing technology; advanced architecture and design concepts for reducing custom fabrication; increasing chip utilization and improving system reliability through fault tolerance and system testability through on-chip testing; advanced CAD techniques; improved silicon materials and fabrication processes; analytical methods for determination of substrate and fabrication induced defects at the submicron level; methods for improving radiation, thermal and mechanical stress tolerance; establishment of design standards and interface requirements; new device, gate and circuit structures; techniques for documentation and methods for improved simplified utilization and testing.

In essence all of these efforts can, and most should, be carried out under the vertically integrated efforts in the main program. VHSIC-III efforts are intended to reduce the risk in the overall program through many innovative efforts on specific problems of concern. Phase III results will be available to all VHSIC contractors.

Applications

The VHSIC Program objective, at the device level, is stated in terms of functional throughput (the product of switching frequency and the density of logic gates). The goal here is several orders of magnitude of improvement over the most advanced circuits which were in production when the program was started--a very challenging and exciting prospect. But underlying these technical advances are vital, sobering, military realities.

In general, a new breed of military equipments is emerging which will change the way in which military force is applied and may even determine the balance of military power in the decades ahead. These weapon systems, and the command and control apparatus under which they operate, are designed to collect, analyze and rapidly disseminate tactical information relating to the disposition of enemy forces and to attack the most critical targets with precisely delivered munitions. The selective, timely, and precise expenditure of munitions and armaments produce a force multiplication factor intended to reduce any numerical disadvantage which U.S. military forces might face in a future conflict. This force multiplication factor depends upon improved methods of locating and identifying enemy military forces and upon the development of more precise and selective missiles and munitions. The equipments used for these purposes include long range radars in aircraft and satellites; special receivers for intercepting and analyzing enemy radio and radar transmissions; secure, high data rate communications equipment to distribute tactical information concerning the status of our own forces and the disposition of enemy forces; various types of high resolution radar and optical sensors for locating and identifying targets such as ships, tanks, other vehicles, command posts, supply depots, etc.; high precision navigation and target location systems; and "smart" missiles, shells, bombs and other munitions, some of which are guided while others contain autonomous homing devices with their own capability for target localization and identification. All of these equipments make intensive use of signal processing and data analysis. They must, at the same time, be compact, lightweight, reliable, low power and relatively inexpensive. This combination of attributes will uniquely characterize the monolithic large scale integrated circuit for military application.

The classes of military equipments in which the integrated circuit assemblies are crucial include processors of sensor signals, digital communications components (such as frequency signal analyzers), and numerous other equipments which contain embedded processors or computers.

The type of weapons and weapon delivery systems in which the equipments play a vital role are: the strategic and attack submarines, with acoustic beam formers, signal analyzers and target signature files; airborne early warning (AEW) systems (the Navy E-2C and the Air Force AWACS), with radar signal processors and data encoders; advanced interceptor and interdiction aircraft such as the F-14, F-15, F-16, F-18, A-10, with radar signal processors and synthetic displays to aid in air-to-air combat; all weather ground strafing and bombing; tactical ballistic and cruise missiles such as PERSHING II, TOMAHAWK, etc., with sensor processors for precision terminal

guidance; the so-called "fire-and-forget" missiles which can be launched from a safe distance but will automatically locate, detect and attack targets such as tanks.

The integrated circuit performance levels required for military systems can be characterized approximately by the functional throughput rate (FTR) defined as the product of the number or density of logic gates on the chip and their switching rate. A typical advanced commercial microprocessor contains the equivalent of 6,000 to 8,000 logic gates on a 7.5 mm square chip which are switched at an average rate of 5×10^6 Hertz or so, with an FTR of about 4×10^{10} gate · Hz/chip or 7×10^{10} gate · Hz/cm^2. By comparison, several types of military equipments require that the FTR be increased by two orders of magnitude or more. This increase is to be achieved by technology advances of several sorts including circuitry innovation (essentially more powerful and compact embodiments of elementary logical elements), increasing circuit density, increasing circuit speed, and increasing total active area per chip. The ratio between circuit chip throughput and total power dissipation is directly related to the minimum dimensions of circuit elements. This relationship accounts for the emphasis on the advancement of lithographic technology and the keen interest in the scaling of the various integrated circuit technologies. This is a large potential for increasing FTR by scaling of the minimum dimensions. Previous progress has been based almost completely on scaling.

The minimum total number of chips required to realize a system is determined by the ratio of the system instruction rate to the mean equivalent instruction rate per chip. This relationship makes it possible to estimate the total weight and power consumption of integrated circuit assemblies in terms of device feature sizes. Given systems support cost coefficients for weight and power (including both prime power and cooling), the systems support cost can be determined in relation to feature size. Current aircraft systems cannot afford to devote more weight, power, volume or cooling to their electronic systems. For example, the total processing load for all avionics in some types of next generation aircraft systems has been estimated at 3×10^9 operations per second, typically with 16 bit words. A throughput rate of this magnitude in a small aircraft is not feasible using contemporary military integrated circuits. Instead, advanced integrated circuits which would provide about two orders of magnitude higher throughput in relation to power, weight, failure rate, are needed. The VHSIC Program intends to make such integrated circuits available to military system designers.

Throughput Rates

Bounds for the total throughput rates for various equipments and systems are summarized in Table A1-1. The lower bounds are representative of the most advanced currently operational state-of-the-art equipment while the upper bounds refer to systems still in planning and requiring VHSIC component development.

Table A1-1. Throughput Rates in Millions of Operations Per Second

Programmable A/J Communications	10 to 500
Optical Surveillance Equipment	100 to 2,000
Radar Processors	50 to 1,000
Missile Sensors and Guidance	2 to 50
Acoustic Processors	100 to 1,000
Airborne Early Warning Systems	100 to 3,000

Military needs for integrated circuit subsystems are characterized by high throughput rates in relation to size, power comsumption, etc. They also require low failure rate at the board and assembly level, special temperature and radiation tolerance, as well as spares and other operational support throughout the operational life of the system. Aircraft, submarines and ships often remain in service for 30 years or more, well in excess of the economic life of some (if not all) integrated circuit technologies. Finally, military systems designers are often deterred from the use of integrated circuits by managerial and institutional constraints such as long development and funding cycles (freezing parts lists years in advance of full production); expensive documentation and qualification. None of these constraints fit well with rapid changes in component technology.

Failure Rates

The necessity for low failure rate at the system level reaches its extreme in satellite systems, which must remain operative for several years to amortize launch costs. To achieve fault tolerance, i.e., system failure rate lower than the component failure rate, without maintenance, necessitates component redundancy and some form of automatic failure isolation, possibly

in a hierarchial structure. In varying degrees, the same attributes are advantageous in other military equipment whose operational environment makes extensive logistics support infeasible.

In some military applications the requirements for radiation hardness override all other consideration and could preclude the use of certain circuit technologies (such as NMOS) which might otherwise be attractive.

All of these considerations have thus far delayed the extensive application of large scale integration in military equipment.

However, the IC industry has been undergoing market and structural changes which improve this prospect in several respects. The vertically integrated military system suppliers have generally extended their capability to develop circuits specifically for military application by the acquisition of modern IC manufacturing facilities and constant upgrading of computer aided design (CAD) techniques which reduce the cost and risk associated with the development of new circuits. In many instances, these captive IC facilities include development laboratories which are at the forefront of very high speed integrated circuit technology. At the same time, the commercial market for high performance circuits has grown significantly. In response to this demand the IC manufacturers have upgraded products and added new ones; notably 16 bit microcomputers, hardware macros (such as multipliers), improved bit slice components and various forms of semicustom circuits. The general purpose programmable microcomputers are now at the threshold of medium performance military applications such as venice abstraction, and portions of the JTIDS and Global Positioning Satellite receivers. The capabilities of the microprocessor and bit slice based assemblies can be substantially augmented by the development of a compatible set of hardware macros (such as one cycle function calculators, automatic sort-and-merge memory stacks, FFT butterfly, interpolator, etc.). This could continue a trend toward the use of specialized circuits ("super cells," "functional partitioning") of which the dedicated multiplier chip is a pre-eminent example. The use of hardware macros has been made economically feasible by LSI technology.

The utilization in military systems of microcomputers and bipolar bit slice based assemblies also increases areas of commonality between the military and commercial markets, which gives the military system suppliers a larger production base to draw from; alleviates the funding, schedule, documentation and qualification obstacles; and increases the likelihood of continued availability of spares and of

"technology transparency," i.e., the availability of compatible replacements as more advanced IC technologies enter production. Furthermore, the use of these circuits preserves existing assets of software and engineering expertise.

These considerations argue for the maximum re-use of a limited set of broadly applicable circuits well supported by developmental tools including efficient assembly language and microcode compilers from a powerful higher order language such as Ada. Developing the architecture of this set of products and producing them in integrated circuit technologies suitable for military environments is the challenge facing the Department of Defense and the integrated circuit industry.

System Implications

The achievement of the functional throughput rates targeted by the VHSIC Program would translate directly into important performance improvements in many critical types of military equipments. The following represents a few examples:

The Vietnam conflict and the Yom Kippur War brought into focus the limited ability of tactical aircraft to find, attack, and destroy moving vehicles such as tanks and troop carriers. This has prevented superior air power from being translated into a decisive advantage on the ground. This is not due to a failure in airborne overland radar surveillance but in the ability of the surveillance radar to classify targets and to select those which it is cost effective to attack. Also, once the air-to-surface missile has been launched, it must reacquire the target for the precision terminal guidance. The effectiveness of this mode of air-to-ground engagement depends critically upon the range from which the missile can be launched and the success rates (kill probability per round). In fact, the launch range must exceed the range of mobile surface-to-air missiles to avoid excessive losses of pilots and aircraft.

Autonomous missiles which can detect, identify, and fianlly home on tactical targets such as AA batteries, tanks, trucks, troop carriers, command posts are in development. For these systems to function successfully, a series of signal processing operations must be performed in tandem over the course of the attack. The IR image data must be extensively processed to compensate for variations in responsivity of the sensor or for DC restoration, other distortion must be removed or compensated, and dynamic range optimized. Because of the very short reaction time, the pilot must assist in locating the target areas by a series of cueing operations consisting of feature extraction, classification and tracking (stabilizing the display for changing aspect and range). If the missile is to be launched beyond the range at which targets can be

identified from sensor data, then the pilot (with the help of signal processing) selects the target area but, as the missile approaches the target, the missile's sensor must automatically locate and identify a valuable target and complete the terminal guidance. The target detection and recognition process requires operations such as smoothing, edge detection, gradient, connectivity operators, computation of "texture," spot detection and so on.

Altogether, these data p cessing steps require several hundred million computer operations per second, depending on the resolving power of the sensor. The full functional throughput capability per chip that is targeted by the VHSIC Program is needed to provide this amount of processing in the limited available power, weight, and volume of the missile seeker system.

Both functions, target classification and target requisition, depend on digital signal processing. They are key applications targets for VHSIC technology.

Another application of VHSIC technology is acoustic signal processing. Digital processing is used first to form fine receiving beams from arrays of hydrophones. Digital processing improves both the detection sensitivity for quiet targets and the precision with which they can be located. Beam forming is accomplished by a fast-fourier transform (FFT) of the elements of the array. Then the signal from each beam is analyzed into narrow spectral bands by a second FFT to isolate the acoustic signature of each source. Finally the signature is compared to those in a large file to determine correspondence with known criteria. Substantial deck space and power in both attack and strategic submarines are devoted to digital processing of acoustic signals and, even so, not all incoming data can be processed. For this reason, more powerful signal processing will be incorporated into the submarine advanced combat system (SUBACS) using the products of the VHSIC technology.

In airborne ASW (P-3) acoustic processing systems are also limited in performance by their signal processing capacity.

The signal processing operations in the P-3 include beam forming, followed by spectral analysis (FFT) of each beam of the ERAPS array, processing of several DIFAR receivers, and of CASS (Command Activated Sonar System), DICAS, etc. The current P-3 system is processor limited. Under the VHSIC Program signal processors will be developed which will permit full utilization of the acoustic data from all of these systems. Here again, the needed digital processing rate corresponds to several hundred million (perhaps a billion) instructions per second.

A third area in which VHSIC chips will make vital contribution is that of command, control and communication. Reliable secure communication between ground forces, even to the patrol level, will become a reality since it will become feasible to perform voice abstraction and syntheses, encoding and decoding (which demand computational rates exceeding that of major computers of recent vintage) with man-portable equipment (weighing less than 20 lb. including battery pack).

VHSIC chips will add to our ability to communicate reliably (even in the face of determined enemy countermeasures) and with reduced risk of interception and decoding. The former is accomplished by time and frequency dispersion and the latter by encryption, all of which can be performed at the chip level (frequency synthesizers, error correction coders, syndrome calculators, and the like).

System Economics

Although the dramatic economics of large scale integration are now widely understood, the impact of integrated circuit technology on the cost of maintaining effective military force goes beyond the cost of the integrated circuit. The costs of the integrated circuits and their assembly into subsystem is generally small relative to the aggregate cost of qualification of the integrated circuit (for operating temperature range, tolerance to nuclear radiation, etc.), documentation, special test equipment, logistics and operational support and above all, the life cycle costs of the host system which are attributable to its integrated circuit subsystems. Typically, the latter are referred to as system support costs and include the incremental cost of prime power, deck space, air conditioning and so on, which in the case of submarines, missiles, high performance aircraft and satellites, far exceeds the total procurement costs of the integrated circuit subsystems. This is evident through consideration of the cost coefficients which relate the total life cycle costs of a system, to the weight, power, size and reliability of its IC components. For a satellite, for example, the cost coefficient for prime power was (in 1975) about \$2000 per watt and for weight \$5000 per kgm. In a system containing 10^7 transistors, and reduction in average operating power of one milliwatt per transistor resulting from IC technology improvement would amount to a cost reduction of \$20M per satellite for prime power alone whereas the total cost of the circuits themselves would amount to a few hundred thousand dollars. The comparative reliability

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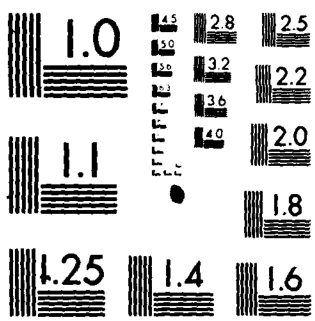

MICROCOPY RESOLUTION TEST CHART
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of assemblies of high integrated circuits also has far reaching cost implications.[1]

System Complexity Problems

Even though the reliability of individual electronic components has steadily improved over the years the complexity of military electronic subsystems has grown even more rapidly--as a result of escalating performance demands--with the consequence that the overall failure rate for aircraft avionics systems has increased to the point that unscheduled maintenance of electronics has become a major cause of operational downtime. This in turn, increases the total number of systems which must be purchased to achieve a specified level of force effectiveness. It is for reasons such as these that the economic impact of advanced integrated circuit technology on Department of Defense programs greatly exceeds its total procurements of integrated circuit components. The point has been reached where the military can no longer devote increased integrated circuit capability to performance improvements alone. Instead, part of that capability must be used to provide built-in test and fault-tolerance because these features have high leverage on operating costs.

As previously stated, U.S. defense posture has been firmly based on using superior technological capabilities as a force multiplier to offset quantitatively superior forces. This policy may in the future be weakened because of the rapid advancements in Soviet military technology, and by availability problems of complex electronic systems. These problems are illustrated by data showing that U.S. military aircraft are mission capable; i.e., in fighting condition, only 1/3 to 2/3 of the time; that up to 2 man-weeks of maintenance may be required after every sortie--or that the first failure occurs 12 minutes into the flight [Ref. 7].

Another drawback of complexity is cost. Because the Phoenix missile costs nearly $1 million, none has ever been fired from an F-14 in a training exercise. Similarly, because an F-14 costs close to $23 million, the Navy will procure only 467

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[1]Systems consisting of large scale integrated circuits (LSIC's) are more reliable than equivalent assemblies of medium scale integrated circuits (MSIC's) not because one LSIC is more reliable than an MSIC (it is not) but because an assembly of LSIC's contains proportionately fewer external interconnections and interconnects are the major source of failure.

rather than the 700 originally contemplated. Of the 467 aircraft that are purchased, only 205 will be effectively operational because of maintenance downtime. It has been estimated that weapon system costs have increased 4 1/2 times every decade.

The electronic advances required to improve rather than degrade the complexity resulting from many system features are not either obvious or easy to achieve but, with VHSIC, are possible. VHSIC must not cause an increase in the support required by the fighting forces or in the maintenance time required for its equipment. The satisfaction of these requirements presents crucial challenges to the architecture and design of VHSIC chips and systems.

Solutions

Increased maintenance and decreased reliability are not inherent in complexity. Integrated circuits have proven this. As the capability built into a given silicon chip has increased from one transistor to 100 thousand transistors, the reliability of the chip has remained roughly constant. In the end, if a system can be built onto a single chip, it can be extremely reliable. Availability problems with some modern weapons systems are caused by a proliferation in the number of parts, in the system software, and in the interfaces. These are consequences of the system design and architecture, and not of the complexity or sophistication.

One solution to the complexity problem for military electronics is to be found in the VHSIC Program. As large assemblies of components are reduced to single chips, as multiple mission functions are integrated into programmable processors, and as military systems achieve a level of commonality in chip usage and move down the learning curve, rapid improvements can be expected. Because of the high geometric resolution demanded by the VHSIC Program, additional area will be available on VHSIC chips for implementing self-repair and built-in-test that will increase reliability and simplify maintenance. The ultimate goal is to create an interface with maintenance personnel that demands less skill to restore a failed system to operational status.

An ultimate goal of the VHSIC Program is to bring us a step closer to an ultimate capability for fabrication of VHSIC chips in a facility that responds rapidly and effectively to new system requirements. The output of such a facility would be chips using a mature technology with high reliability and meeting military specifications. The facility would incorporate a compatible multi-level design process that incorporates testing technology and that is independent of the specific functional requirements being implemented.

With this capability, the interface, both with the military user and with support personnel can be simplified so that these personnel can be served by the system rather than being so overtaxed by system demands that their mission is degraded.

Summary

In summary, the VHSIC Program is a broad, joint service program which is designed to benefit all future DoD systems. Because it has been initiated in response to system and mission needs, i.e., the need for effective force multiplication, it focuses on two major areas. The first is to push the integrated circuit technology of the DoD contractor base to a point well beyond the reach of Soviet system designers.

The second area of VHSIC focus is in the design and architecture of realizable chips and subsystems which maximize reliability, commonality, and performance and which minimize test, maintenance and other support requirements.

If we are successful in these two major objectives then the next generation of weapon systems will provide an effective fighting capability in the field, not just in the vision of the system designer in his laboratory.

LIST OF REFERENCES FOR APPENDIX A

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APPENDIX B

LOGISTICS DESIGN CONSIDERATIONS[1]

To achieve the required level of overall effectiveness for sustained accomplishment of a specified mission or function applicable to any hardware system, design must attain a proper balance between operational and support requirements and features. The development of such a balance involves analysis, evaluations and tradeoff studies within the framework of the system engineering process. It entails repeated review and refinement of emerging support requirements and their probable impact on design objectives, including operational and readiness performance characteristics.

Quantified operational readiness performance requirements serve as a yardstick against which design can be established and support can be defined in terms of assigned tasks and needs. These requirements or key characteristics must be expressed quantitatively, insofar as possible, to measure equipment availability, utilization, downtime, turnaround time, personnel requirements, maintenance manhours per flight (or operating) hour, defined constraints, etc., as appropriate to the equipment type and intended use. It is also important that operational and support requirements and features developed for the system are in context with what is necessary and sufficient (no more/no less than required).

Support considerations as related to system design reflect the following four basic areas:

1. Hardware--prime equipment, spares, tools, test equipment, etc.
2. Software--test tapes, technical manuals, data, etc.
3. People--skills, number of personnel, training, etc.
4. Facilities--buildings, utilities, interfaces, etc.

These four basic areas are evaluated in relation to engineering specialty programs to determine requirements which are to be included in the system/equipment specification as design constraints. Typical examples of engineering specialty

[1]Appendix A to Ref. 6.

programs are: Reliability, Maintainability, Personnel Subsystems, Maintenance Requirements Analysis, and System/Cost Effectiveness. These programs, as well as other engineering efforts are integrated into the initial consideration of system design through an iterative system engineering process controlled by feedback to have proper impact on design decisions.

Maintainability

The first logistics design consideration applicable to the process of developing a hardware system is maintainability, which begins with the definition of preliminary maintenance concepts through postulation of all possible maintenance alternatives within the requirements of the Customer. Such factors as use, deployment, maintenance levels and functional requirements are evaluated. Based on the preliminary maintenance concepts and Customer-specified quantitative values related to permissible downtime, turnaround time, operational availability, etc., maintainability apportionments and predictions are developed for each subsystem, LRU, and/or functional loop of the prime hardware system by maintenance level. The apportionments are included in design specifications as maintainability goals. Most maintenance, with the exception of servicing consumables, pre-operating and post-operating inspections and such, are directly related to the reliability of the hardware. For this reason, tradeoffs are performed between reliability and maintainability to establish proper balance within the context of determining what is necessary and sufficient. As design progresses, maintainability features are defined for incorporation into the hardware design. This is accomplished through development and inclusion in specifications of maintainability design guidelines evolving from maintainability design analysis and trade studies, and from requirements determined through other engineering specialty programs. Maintainability features include, but are not limited to:

1. Accessibility applicable to all maintenance significant items down to the respective throwaway level.
2. Standardization
3. Interchangeability
4. Number, type, and location of adjustment and calibration devices
5. Number and location of test points
6. Number, type, and location of self-test features
7. Number, type, and location of maintenance displays and controls
8. Safety features
9. Labeling
10. Connectors

Throughout the remainder of the design and development phase, a continuing analysis is performed as additional information accumulates to verify that specified maintainability features have been incorporated in the design and that they are appropriate to ensure that established quantitative maintainability goals can be met.

Concurrent with the start of maintainability design analysis, a systematic support analysis is begun. The purpose of this analysis is to identify required support resources and, through tradeoff studies between design and support requirements, establish an optimum cost/effectiveness between equipment functional and support requirements. Again, the respective requirements are within the context of what is necessary and sufficient. The required resources are defined through the integrated efforts related to Maintainability Analysis, Maintenance Requirements Analysis, Personnel Subsystem Requirements Analysis, and Supply Support Analysis.

Maintenance Requirements Analysis

Maintenance Requirements Analysis defines the maintenance functions and supporting requirements necessary to maintain the particular system and equipment at each level of maintenance in its prescribed state of operation. Maintenance functions include checkout, servicing, inspection, fault isolation, replacement, repair, modification and overhaul. Concurrently with hardware design and updated as design changes, specific maintenance actions and resources requirements needed to support those actions are identified by systematic and detailed analysis. Based on the preliminary maintenance concept developed during the early phases of design, the degree to which these various functions are to be performed by organizational, intermediate/field, or depot level maintenance is identified through an iterative analysis and tradeoff process. This analysis includes optimum repair level analysis which determines the most cost/effective level at which each respective function shall be performed considering turnaround times, resource requirements, deployment, etc., to meet stipulated readiness requirements. The design is also reviewed to determine functional discard-at-failure for hardware levels beyond which repair is not economical. This throwaway level to be selected for a given design is dependent on a great many factors, and may be established at any point between the entire system and any of the piece parts of its subsystems. Somewhere between these two extremes is the optimum level. Selection of the throwaway level depends on the cost of initial hardware, its relative contribution to availability requirements, and the user's support cost over the life of the system. Tradeoff procedures are employed to determine the optimum cost/effective throwaway level.

As a coordinated effort with the Maintenance Requirements Analysis and maintainability design analysis, specific support and test requirements and parameters are identified and documented for the purpose of baselining the Support and Test Equipment requirements. During design of the Support and Test Equipment, the same logistics considerations, processes, procedures and interfaces apply as those pertaining to the prime equipment.

The iterative Maintenance Requirements Analysis process also identifies and describes tool requirements, maintenance facilities and facilities interface requirements, and logical spares and repair parts candidates by maintenance level. Through evaluation of prime equipment utilization and maintenance return rates, qualification of tools and Support and Test Equipment needs by time and place is determined, and facilities loading to establish adequacy and utilization can be identified. By weighing the requirements thus identified and developing alternatives for different approaches, the maintenance concept can be further refined and influence hardware design as necessary to minimize the life cycle cost of the system. This process also ensures that the optimum mix of design and support requirements remain in context with what is necessary and sufficient.

Maintenance Requirements Analysis evaluation factors include, but are not limited to:

1. Discard levels
2. Repair levels
3. Maintenance repair locations
4. Tool and test equipment characteristics and requirements
5. Time line requirements
6. Diagnostic test levels and sequence
7. Calibration requirements
8. Repair turnaround times
9. Tool and test equipment utilization rates
10. Maintenance return rates
11. Maintenance facility requirements
12. Maintenance facility interface requirements
13. Operational Concepts

Personnel Subsystems

Based on documented data developed during the Maintenance Requirements Analysis, personnel subsystem requirements are determined. Because Personnel Subsystem Test and Evaluation (PSTE) is a demonstrable parameter imposed by many DoD contracts, this logistics design consideration is of utmost importance. PSTE is performed by Customer personnel utilizing production-configured prime equipment, as well as support and test equipment. The demonstrable parameter is normally expressed in maintenance manhours per flight hour (or operating

hour) and is a function of the equipment reliability and maintainability (covered previously herein), prime equipment utilization rates, the quantity and quality of the personnel, tools and test equipment provided, facilities, and the technical manuals and procedures available. It is noted that only active time applies; administrative time is neglected. It can be recognized that if any one of the specified personnel subsystem requirements is less than necessary and sufficient; e.g., not enough training, wrong skill level, procedures not available in technical publications or available but unclear, etc., the availability rate or target cannot be achieved. On the other hand, if the defined personnel subsystem requirements are excessive, increased life cycle cost will result. Therefore, close integration on an iterative basis must occur between personnel subsystem requirements analysis/evaluations and all other systems engineering processes in order to provide not only "design to" requirements, but also to optimize the support system.

The initial personnel subsystem requirements are derived from examination of the maintenance tasks identified through Maintenance Requirements Analysis and are further developed through a repeated process of evaluations, determinations, tradeoffs, and feedback. Available skill levels within the respective user organizations are evaluated for direct applicability with no additional, minimum additional or extensive additional training. Based on the definition of recommended skill levels, training requirements are established and required training equipment is identified and documented. During design and development of training equipment, the same logistics considerations, processes, procedures and interfaces apply as those pertaining to the prime equipment.

Through further evaluation of defined maintenance tasks, associated timelines, and maintenance loading, the quantitative personnel requirements are defined and updated as design and maintenance analysis progresses. It is also important that a closed-loop condition exist between maintainability, maintenance requirements, and personnel subsystem analyses to influence equipment design and to establish proper balance between operational and support requirements as it affects life cycle cost and operational readiness.

Concurrent with definition of qualitative and quantitative personnel requirements, training requirements are defined for each applicable skill level. As the analysis progresses, training plans, curricula, and training material is developed. Also, training facilities requirements are identified and documented, based on requisites imposed by such factors as class sizes, training equipment interfaces, safety requirements, etc.

It should be emphasized that, as specified by DoD documents, Human Engineering is included as a personnel subsystem element. Even though human engineering is not the organizational responsibility of Logistics per se, a definite interface responsibility exists. Human engineering is the application of knowledge concerning human capabilities and limitations to achieve system performance requirements by the optimum use of personnel as a system component. Thus, human engineering, as a design parameter, interfaces not only with other personnel subsystem elements, but also with maintainability.

Technical publications provide the link between personnel and equipment. They include operating and maintenance instructions, inspection and test procedures, and other forms of audio/visual presentations required to guide people performing operations, maintenance, and support tasks. Technical publications considerations are involved in design and support tradeoffs, tests and demonstrations. They are based on operational readiness requirements and goals and must be in consonance with alternative concepts being examined for other support elements. Technical publications requirements and coverage are determined from Maintenance Requirements Analysis data and are developed in accordance with Customer-imposed specifications, procedures, and processes. During PSTE, technical publications are verified to ensure that they satisfactorily provide personnel with the information necessary to conduct operations and maintenance in support of established performance goals. The verification actions also test the publications for durability during use, accuracy and completeness of information, clarity appropriate for use at the intended skill level and maintenance level, ease of access and updating.

Personnel Subsystem Characteristics include, but are not limited to:

1. Personnel index
2. Personnel skill levels
3. Minimum training requirements
4. Training equipment characteristics and requirements
5. Health and safety requirements
6. Types and levels of technical publication requirements

Supply Support

Maintaining operational readiness under diverse conditions of equipment use depends directly on the availability of the right supplies at the time and place they are needed. Therefore, supply support is an essential element of the integrated logistics effort to provide a support system within the context of what is necessary and sufficient.

During the Concept Formulation Phase, the sparing concepts and the provisioning criteria for the particular equipment must be developed. The optimum sparing models are based on the operational and maintenance factors known or developed at that point. Such a model includes consideration of quantitative and qualitative requirements to include the proper spares mix for that particular equipment in its operating and maintenance environment. This is an iterative process that is carried through the Definition, Development, and Test phases with feedback into the system engineering process to ensure mission effectiveness and cost effectiveness within the limits of necessary and sufficient spares.

The supply planning for spares and repair parts is based on technical inputs from the Maintenance Requirements Analysis; e.g., system/equipment utilization rates, operating hours, failure rates, required field repair rates, locations, and selected maintenance items critical to safety and mission accomplishment. From listings of logical spares candidates determined as part of the Maintenance Requirements Analysis, quantitative spares requirements and proper spares mix are defined in concert with the maintenance concept.

Factors influencing quantitative spare requirements include, but are not limited to, the following considerations:

1. Probability of having a good spare on demand
2. Mission essentiality of the spare
3. Repair ratios
4. Pipeline times
5. Failure incident
6. Repair yield rates
7. Item Condemnation rates
8. Spares mix

Factors influencing qualitative spare requirements include, but are not limited to, the following considerations:

1. Spare sell-off criteria
2. Shelf life
3. Storage requirements
4. Transportability

Once these quantitative and qualitative factors have been developed and considered, their impact on all other ILS elements must be assessed. This involves a prompt feedback to systems engineering analysis to determine whether factors which initiated supply support calculations should be reassessed and modified. The entire feedback action must have the benefit of a high-speed computerized tradeoff and assessment if logistics design considerations are to keep pace with

the evolving design baseline in a major system/equipment program. Math and computerized models described in Appendix B are employed where volume of information and time constraints dictate.

Support System Integration Analysis

In the course of assessing quantitative and qualitative supply support information in the system engineering process, fallouts involving interactions with all other ILS elements may require a complete support system integration analysis. From a practical standpoint, this type of analysis is best accomplished as a subroutine to total systems integration. Thus, the Support System Integration Analysis would encompass a tradeoff of the products of the maintainability analysis, the maintenance requirements analysis, the personnel subsystem analysis and the supply support requirements analysis. This Integration Analysis provides optimization of the maintenance and support mix within the context of what is necessary and sufficient to support the product. In addition, it serves as a process to evaluate, on an integrated basis, all logistics design considerations.

Through the maintainability analysis segment of the Integration Analysis, specific logistics design considerations are identified for tradeoff against design constraints in the system integration process. The final product of this action is included in system, subsystem and configuration item specifications as maintainability design criteria and a logistics resource requirements package. This package reflects the resources required to maintain and support (and possibly operate) the system in its intended environment and in consonance with the final design baseline specifications. Any change in the baseline calls for a review of resource requirements and vice versa.

Beginning with first operational use, logistics support data become available to confirm the composite requirement or call for re-assessments based on an integration analysis. Thus, the iterative process used in establishing logistics design continues throughout the life cycle of a system/equipment and ensures that optimized maintenance and support resources are applied to the program.

APPENDIX C

LOGISTIC SUPPORT CONSIDERATIONS[1]

10.1 INTRODUCTION

> If our strategic and logistic plans are to be brought into timely harmony they must be fully integrated from their inception through their final execution. This process of integration requires certain formal planning procedures and also the organization of systems of information and of programming.
>
> Henry E. Eccles, RADM, USN (Ret), [Ref. 1]

The above quotation from Admiral Eccles' book appears to be quite prophetic in light of the interest and emphasis by the Department of Defense and industry in the subject over the past 17 years.

Every study of military strategy and tactics emphasizes the importance of effective logistic support. This importance does not diminish when the support objective is space exploration or other scientific expeditions. With the advent of manned space flight and manned interplanetary exploration, the need to fully understand the logistic and economic considerations involved becomes increasingly acute.

I would like to quote an entry from the log of the USS Constitution entered in the years 1779-1780 which relates to the supply management facet of the logistics discipline. The excerpt is as follows:

> On the 23rd of August, 1779, the United States Ship Constitution set sail from Boston. She left with 475 officers and men; 48,600 gallons of fresh water; 7,400 cannon shot; 11,600 pounds of black powder; and 76,400 gallons of rum on board. Her mission was to destroy and harass English shipping.
>
> Making Jamaica on 6 October, she took on 826 pounds of flour and 68,300 gallons of rum. Then

[1]Chapter 10 of Ref. 8. All references cited herein are separately identified at the end of this appendix.

she headed for the Azores, arriving there on 12 November. She provisioned with 550 pounds of beef and 64,300 gallons of Portugese wine. On 18 November she set sail for England.

In the ensuing days she defeated five British men-of-war and captured and scuttled 12 English merchantmen. By 27 January her powder and shot were exhausted.

Unarmed, she made a raid on the Firth of Clyde. Her landing party captured a whiskey distillery and transferred 40,000 gallons on board by dawn. Then she headed home.

The Constitution arrived in Boston harbor on 20 February 1780 with no cannon shot . . . no powder . . . no food . . . no rum . . . no whiskey . . . but with 48,000 gallons of stagnant water.

If you are interested in consumption rates, this figures out to be approximately 2.9 gallons of spirits per man per day.

Aside from the humorous aspects of these statistics, the need for a thorough analysis of logistics demands to support mission operations is clearly evident. Perhaps the Constitution should have been provisioned with additional shot and powder and less water. The determination of type and magnitude of logistics demands together with the means for satisfying them are the very heart of the logistics effort.

Logistic support means many things to many people. There are those who view logistics as a large assortment of spare parts and components. Others consider logistics as primarily a maintenance problem, while still others hold that logistics is essentially a transportation problem. All of these viewpoints are partially correct; however, they do not pursue the subject far enough to recognize the scope of logistic support and its impact in determining mission success or failure. The Integrated Logistic Support viewpoint focuses attention on the logistics engineer and logistician and their respective roles in the total system acquisition process and the system life cycle...

What is Integrated Logistic Support about? The purpose of ILS, as promulgated by DoD, is to assure that effective logistic support is planned, acquired, and managed as an integrated whole and that logistic support will be

given consideration on a level equal to the prime system from the outset of system planning, development, and acquisition.

The dollar investment that Department of Defense agencies and NASA place in their annual budget requests for the support of existing systems far outweighs the cost of development and production of such systems. This situation poses a major challenge to those who have logistic support responsibilities. Because of the recognition of the close coupling (but by no means the only one) of life cycle cost with logistic support, the potential exists to do something about it during system development by means of ILS/LCC tradeoffs.

10.2 BACKGROUND

Much of the interest and impetus in "Integrated" Logistic Support stems from the publication in June of 1964 of DoD Directive 4100.35 entitled "Development of Integrated Logistic Support for Systems and Equipments." [Ref. 2] This document gave emphasis at DoD level to fully coordinated logistic support consideration concurrent with the development of systems and equipments, starting as early in the life cycle as concept formulation.

In a study of the cost-effectiveness of alternative support plans for major weapon systems, the Logistics Management Institute found

> Prior to the issuance of DoD Directive 4100.35, and partly as a result of the institution of the System/Project management concept and the DoD Programming System, there was a growing emphasis in the Defense Department on the need of early and integrated logistic support planning using quantitative methodologies. Although logistic support planning has, of necessity, always been performed for weapon systems, it has been marked by an absence of quantitative methodologies and measured consideration of alternatives during the conceptual phase of a weapon system's life cycle. Later in the life cycle the planning has been done by functional specialists often working in isolation from each other without measures which enabled them to relate decisions to their impact on logistic support as an integrated whole. By functional planners we mean supply, maintenance, procurement, production, transportation, packaging and personnel

specialists, as well as design engineers and "operational" planners (logistic annexes to war plans). [Ref. 3]

Shortly after publication of DoD Directive 4100.35, the DoD Equipment Maintenance and Readiness Council established an ad hoc committee, with both military and industrial representation, to explore means for the implementation of the directive including the development of methodology and tools. Nine tasks were pursued by nine subcommittees for about a year. The recommendations of the Ad Hoc Committee resulted in the establishment of a DoD ILS Working Group. With the assistance of Logistics Management Institute, members of this working group, representing the military services, prepared and issued a coordination draft of an ILS Planning Guide in October 1968.

In October 1970, DoD Directive 4100.35 was reissued to reflect lessons learned from experience with the previous documents as well as improvements to the systems acquisition process. It stressed as policy the use of a systems approach "for planning, analyzing, designing and managing the incorporation of logistic support into the acquisition of systems" starting with the Conceptual Phase [Ref. 4]. DoD Directive 4100.35 was superseded by DoD Directive 5000.39 in January 1980 [Ref. 5] to bring it in line with the latest version of DoD Directive 5000.1 on Major System Acquisition.

10.3 CONCEPTS, DEFINITIONS AND LOGISTIC ELEMENTS

10.3.1 System and Element

The identification of the scope of ILS and its interfaces, and the definition of the elements of ILS are prerequisites to achievement of the tasks leading to successful implementation of integrated logistic support as a systems discipline. Planning for and developing ILS systems, predicting and measuring ILS cost-effectiveness, effectively generating and communicating ILS information, and assigning responsibilities so ILS can be efficiently managed--all these require precise, consistent, working definitions of an integrated logistic support system.

We have previously defined a system as a set of elements organized to perform designated functions in order to achieve desired results. The set of elements comprising a system include personnel, equipment, meteriel, facilities, and information.

The total operational system with which the designer and user is concerned can be split into the prime mission

system and the support system. The prime mission system is that set of resources and functions required to perform the mission with which it is concerned. The logistic support system is that set of resources and functions required to keep the prime mission system operationally ready to perform its job. The word "integrated" in ILS means that both the prime mission system and the logistic support system (that is, the total operational system) must be considered together during the planning and development phases of system acquisition from the earliest concept formulation and definition phases.

The resources and functions which make up a system are often called system elements. In the case of logistic support systems the functional elements are generally concerned with maintenance and supply activities while the resources are concerned with maintenance and support personnel, test and support equipment, facilities, logistics data, and spares, repair parts and consumables. More will be said of this in a later section.

10.3.2 Logistics, Logistic Support, and Integrated Logistic Support

Logistics is one of those words which mean different things to different people. If we are to discuss it meaningfully, therefore, it is essential that we be able to agree on an acceptable definition. A good place to start, perhaps, is the dictionary. Webster's dictionary [Ref. 6] provides the following definition:

> Logistics - the procurement, maintenance, and transportation of military materiel, facilities, and personnel.

The Joint Chiefs of Staff dictionary defines logistics as [Ref. 7]:

> The science of planning and carrying out the movement and maintenance of forces. In its most comprehensive sense, those aspects of military operations which deal with:
> a. design and development, acquisition, storage, movement, distribution, maintenance, evacuation, and disposition of materiel;
> b. movement, evacuation, and hospitalization of personnel;
> c. acquisition or construction, maintenance, operation, and disposition of facilities; and
> d. acquisition or furnishing of services.

Admiral Eccles [Ref. 1] offers the following:

> Strategy deals with the determination of objectives and the broad methods of their attainment;
> Logistics deals with the creation and sustained support of weapons and combat forces;
> Tactics deals with the specific employment of weapons and forces toward the attainment of the objectives of strategy.
>
> Or, stated somewhat more simply:
> Strategy and tactics provide the scheme for the conduct of military operations; logistics provides the means therefor.

If we examine each of these definitions carefully, we find that they include not only resources (materiel, facilities, and personnel) and activities (support, maintenance, transportation, distribution, storage, disposition, etc.) but also such words as procurement, design and development, acquisition, and creation. Further, these definitions do not differentiate between the prime system and its functions and the support system and its functions. They include, at least by implication, everything--the whole ball of wax. Even more, they include all activities of the System Life Cycle.

There are still other definitions of "logistics" and what it includes, but the above definitions are sufficient to convey the notions. Now, the words "logistic support" are a combination which is used together and with which we are concerned in this course. What meaning does this word combination convey and is such meaning different than that just described for logistics? I submit that logistic support, as it is typically used, separates out the planning, design, production, and operation of support resources and activities from the planning, design, and production of the prime mission resources and activities. That is why we have had our logistic support resources and activities planned and designed in a fragmentary, often after the fact, fashion with little coordination among these support elements or with the prime mission system elements.

By original DoD Directive 4100.35 defined not logistics but "integrated logistic support" as "a composite of the elements necessary to assure the effective and economical support of a system or equipment at all levels of maintenance for its programmed life cycle."

It further stated that its primary objective was "to assure that the development of effective support for

systems and equipments is systematically planned, acquired, and managed as an integrated whole (by interlocking the elements of logistic support) to obtain maximum materiel readiness and optimum cost effectiveness."

10.3.3 Logistic Elements

The elements of integrated logistic support were listed in the original version of DoD Directive 4100.35 as

1. Planned Maintenance
2. Logistic Support Personnel
3. Technical Logistic Data and Information
4. Support Equipment
5. Spares and Repair Parts
6. Facilities
7. Contract Maintenance.

An examination of these elements and their definitions reveals the major flaw in that directive, that it is almost completely maintenance oriented. Thus, it tends to equate the two as, for example,

$$\text{logistic support} = \text{maintenance.} \tag{1}$$

But, while it is true that maintenance is a major part of logistic support, and for many systems the most significant, there is also a need to supply systems with other items in addition to spares and repair parts. These include consumables such as food, fuel, ammunition and similar items, supply equipment and facilities for handling, storing, distributing, and transporting both maintenance related and non-maintenance items, inventory data, and the many other items which generally fall under the category of supply support. Thus, a more proper definition of logistic support could be summed up as

$$\text{logistic support} = \text{maintenance} + \text{supply.} \tag{2}$$

This flaw was recognized by the DoD Ad Hoc Committee to implement DoD Directive 4100.35, for in its report of August 1965 it stated "there is a need to scrutinize the elements of integrated logistic support listed in DoD Directive 4100.35 to determine whether they truly constitute a well-defined support package." The committee concluded that further examination of these elements was required.

This led to the establishment of the DoD Working Group. This group recognized the nature of the problem, that, in addition to the fact that logistic support is concerned with support activities (maintenance and supply support) and

support resources (people, materiel, equipment, facilities, and data), the word "integrated" added as a modifier involves interfaces with management (funding and management data) and with system design (maintainability and reliability, among others).

Extending the definition of logistic support and integrated logistic support to include the above notions results in the modification of equation (2) as follows

$$\text{logistic support} = (\text{maintenance} + \text{supply}) \times (\text{activities} + \text{resources}). \qquad (3)$$

Let us now add the word "integrated" and define it to mean

Integrated (I) = Cost-effective planning, acquisition, and management

and we get

$$\text{ILS} = (\text{Cost-effective planning, acquisition, and management}) \times (\text{maintenance} + \text{supply}) \times (\text{activities} + \text{resources}) \qquad (4)$$

This word equation is what I think ILS is all about. It means taking into account from the earliest conceptual phases of the system life cycle the needs of the total system (both prime and support) in an interlocked manner.

Let us return now to a critical examination of logistic elements. The original DoD Directive 4100.35 elements were, once again,

1. Planned Maintenance
2. Logistic Support Personnel
3. Technical Logistic Data and Information
4. Support Equipment
5. Spares and Repair Parts
6. Facilities
7. Contract Maintenance

The first and last are activities, specifically maintenance activities. The middle five are the five categories of resources. What are the difficulties?

First, planned maintenance sounds like "scheduled" or "preventive" maintenance. It was an unfortunate choice of words. The Navy, for example, has what is called a Planned

Maintenance System (PMS) which is specifically concerned with scheduled maintenance. If one reads what is meant by Planned Maintenance in DoD Directive 4100.35, one finds that the intention was not what the words imply but really planning for maintenance. The DoD Working Group changed this name to Maintenance Planning.

Second, Contract Maintenance does not really belong in the list of elements. The fact that the customer might contract out some maintenance activities instead of performing them within his own organizational capabilities is part of maintenance planning and not a separately designated element. Again, the DoD Working Group realized this and eliminated it as a separate element.

There is nothing wrong with the listing of resource elements except that they must be broadened to include supply resources as well, as indicated by equation (3).

Finally, supply activities must be added as logistic elements.

As a result of its analysis, the DoD Working Group promulgated an ILS Planning Guide, DoD 4100.35G [Ref. 8]. It revised the list of logistic elements to be

1. Maintainability and Reliability
2. Maintenance Planning
3. Support and Test Equipment
4. Supply Support
5. Transportation and Handling
6. Technical Data
7. Facilities
8. Personnel and Training
9. Funding
10. Management Data

Here again we have a mixture. Funding and Management Data are really not logistic elements in the same sense as the others are. They are elements of support management and are, therefore, important ingredients of support planning. Funding includes the important and strong interface between logistic support and life cycle costs. Management Data includes the important interface between support planning and system design/operation management, reviews, and coordination.

Similarly, Maintainability and Reliability are system design elements, but obviously have a very close interface with ILS planning. There are other important system design interfaces worthy of note such as human factors, safety, and standardization, but maintainability and reliability are essential.

Returning to the DoD 4100.35G list of ILS elements, we find that items 1, 9 and 10 are interface items with system design and management and items 2 through 8 are the primary internal concern and responsibility of logistic support. Items 2, 4, and 5 are concerned with logistic support activities and items 3, 4, 6, 7, and 8 are concerned with support resources.

Note the following changes and improvements over the list of elements contained in the original version of DoD Directive 4100.35.

a. The list of elements includes supply support as well as maintenance and is, therefore, better balanced.
b. Recognition is given to the important interfaces with system design and management.
c. Maintenance planning is used rather than planned maintenance to remove the ambiguity as to what is meant.
d. Supply support is used instead of spares and repair parts to include all supply resources. It also includes supply support activities, thus is a combined resource-activity element.
e. Transportation and handling is added as an additional element, perhaps because it was easily neglected.
f. Contract maintenance has been eliminated as a separate element since it is implicitly included in maintenance planning.

The DoD 4100.35G Planning Guide was a step forward in the evolution of integrated logistic support as a system discipline. Let me emphasize, however, that this guide was meant as a management and planning tool, "a 'road map' of typical logistic actions to be accomplished during the life cycle of a typical equipment program" [Ref. 8]. It did not provide the detailed methodologies and techniques for performing the activities charted in its road maps. These methodologies and techniques, such as logistic support/maintenance engineering analysis, provisioning, manning and training analysis, inventory control, life cycle costing and others are the concern of the technical specialists within the logistics discipline.

When DoD Directive 4100.35 was reissued in 1970, the problems which arose (many of them organizational) with the use of the words Reliability and Maintainability as well as Funding and Management Data caused a further revision to the list of logistics elements. The revised list of elements were:

1. The Maintenance Plan
2. Support and Test Equipment
3. Supply Support
4. Transportation and Handling
5. Technical Data
6. Facilities
7. Personnel and Training
8. Logistic Support Resource Funds
9. Logistic Support Management Information.

It further specified better the logistic support planning, acquisition, and management considerations which should be given in each of the system life cycle phases.

DoD Directive 5000.39 [Ref. 5] again changed the list of ILS elements to the following

1. The Maintenance Plan
2. Manpower and Personnel
3. Supply Support (including initial provisioning)
4. Support and Test Equipment
5. Training and Training Devices
6. Technical Data
7. Computer Resources Support
8. Packaging, Handling, Storage and Transportation
9. Facilities

Note that the changes are more cosmetic than substantive. For example, personnel and training has been separated into two categories: (1) manpower and personnel, and (2) training and training devices. One might rightly ask, "What is the difference between manpower and personnel?" In the case of training and training devices, one might wonder whether training devices were not previously considered as part of Support and Test equipment. Perhaps this had been neglected in the past and, therefore, included now for emphasis. Similarly, packaging and storage was usually considered as part of either handling and transportation or supply support. And supply support should automatically include initial provisioning.

Note, especially, the removal of Logistic Support Resource Funds and Logistic Support Management Information as logistic elements.

10.4 ILS PROGRAM PLANNING AND THE SYSTEM LIFE CYCLE

Integrated Logistic Support is the management process by which all logistic elements required to effectively support a system are brought into balance, not only with each other, but also with the design of the system to be supported. This

requires that logistic support considerations be included in all phases of the system life cycle starting with concept formulation. The emphasis on an "integrated" approach to the logistics discipline results in certain implications for logistic support program planning.

Blanchard's book [Ref. 9] adopts the system life cycle as the basis for logistics engineering and management.

Each of the military services has reacted to the issuance of DoD Directive 4100.35, first by issuing its own implementing instructions, and second by instituting internal efforts towards defining, in detail, procedures and responsibilities for the carrying out of ILS programs and plans. For example, NAVMATINST 4000.20 defines Integrated Logistic Support as "an improved planning process designed to provide more timely and effective support of military weapons systems and individual equipments" [Ref. 10]. It further stated that "Each act and decision made throughout the weapons acquisition process of necessity affects the logistic support of the end item to be produced. Growing from this fact is the requirement, ...that the individual responsible for acquiring the end item must be held accountable for the logistic support planning as well. This will reduce the current tendency to design and produce equipment without adequate recognition of real and continuing logistic costs and constraints... The process requires that decisions made during the concept formulation, contract definition, and development phases of the weapons system and equipment acquisition process shall take into account the logistic implications of those decisions."

In terms of the systems approach, one must look at the requirements of the total system. The total operational system consists of a prime system, the object of which is to carry out its various missions successfully, and a support system, the object of which is to continuously keep the prime system in a state of readiness to successfully accomplish its mission objectives. It is precisely because the prime system and the support system interact so strongly that we must always keep them in balance throughout system design and operation. This is the real message in Integrated Logistics Support. Although ILS is pictured as a management and planning process, it is also a strong system design activity. It is thus necessary to have a logically structured management process and its logically structured counterpart in systems engineering.

The ILS viewpoint focuses attention on the logistics engineer and logistician and their roles in the system life cycle and system acquisition process as a differentiation between the maintenance engineer and the maintainability engineer.

The logistician is a person representing the customer or user and his point of view. He is concerned with the operation of the logistic support system and thus in the determination of logistic support requirements. The logistics engineer represents the producer or design viewpoint. He is concerned with how the logistic support requirements can be implemented as part of prime and support system design to meet the needs of the logistician. Of importance to both the logistician and logistics engineer is the cost-effective tradeoff among the design and operational elements of ILS.

This user-producer viewpoint allows us then to examine the ILS program planning requirements of both the logistician and the logistics engineer.

10.4.1 Logistic Support Analysis

The fundamental policy underlying ILS planning, as stated in DoD Directive 4100.35 was that "a complete system approach shall be used for planning, analyzing, designing and managing the incorporation of logistic support into the acquisition of systems" [Ref. 4]. DoD Directive 5000.39 [Ref. 5] gives additional emphasis to this policy and more specific direction as to the considerations required for logistic support at each phase of the system life cycle in order to satisfy the acquisition milestone decision points.

This latter concept offers an excellent basis for ILS planning methodology. A Plan for Use is a logical starting point for the definition of system requirements and the subsequent development of the system. A Plan for Support, derived from the Plan for Use, is a logical tool for the definition of support requirements and the development of the support system. The obvious interface which will exist between these two plans indicates the need for the early development of each of these and the close coordination required between those responsible for each.

The analytical technique used for logistic support planning is called Logistic Support Analysis (LSA) and is defined by MIL-STD-1388 [Ref. 11]. It defines the logistic support process as follows: "A systematic, comprehensive analysis including the projected service support environment of the system/equipment shall be conducted on an iterative basis throughout the acquisition cycle. This Logistic Support Analysis (LSA) shall be the single analytical logistic effort within the system engineering process, and shall be responsive to acquisition program schedules and milestones. The LSA is a composite of systematic actions taken to identify, define, analyze, quantify and process logistic support requirements." It further states "The LSA shall provide specific

consideration of operator as well as maintenance requirements, and inject system support criteria into the design process at an earlier point in the acquisition cycle."

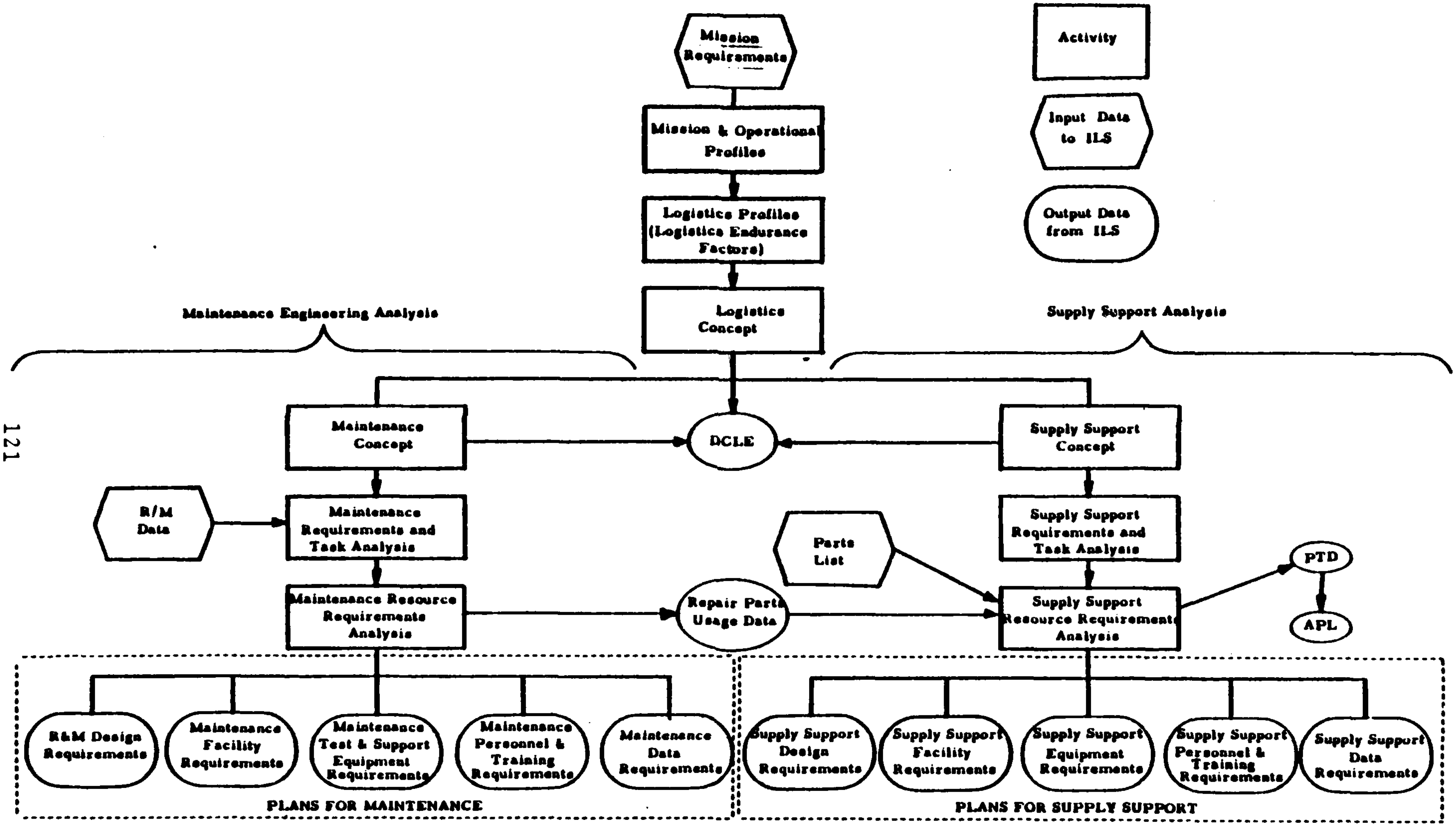
Figure A3-1 illustrates the ILS planning process in flow chart form. In general, logistic support analysis may be divided into two main streams of effort--maintenance engineering analysis and supply support analysis.

10.4.2 Plan For Use

The ILS plan should start at the same time and from the same datum point as the overall prime system acquisition plan. This is the description of mission and operational objectives, parameters, and constraints. No meaningful support plan can be established without this. These, taken together, constitute the Plan for Use. Among the items included are:

1. A description of the operational environment
2. A description of the threat or operational need to be satisfied
3. A description and analysis of mission profiles
4. A description and analysis of system operating modes
5. Mission time factors and system utilization
6. A determination of the duration of the system life cycle including system deployment and overhaul or other out-of-service conditions
7. An elaboration of system effectiveness criteria expressed in mission oriented terms.

Why must the ILS plan start here? Simply because support requirements, whether they be the supply of consumables and spare parts, maintenance, or other logistic support elements, depend on how much utilization the system receives and when it is available for maintenance. For example, if the system is in continuous demand, then obviously its design for logistic support, especially with regard to maintenance, must be such that the system must have high reliability, and normal preventive maintenance must be performed while the system is operating, for example, by the use of switchable, redundant systems--an operating system and a standby system. The FAA has used this philosophy for years for its Air Traffic Control systems. If, on the other hand, the system has time periods when it is not required for use, then the logistic support and maintenance planning requirements may be different. Further, quantitative effectiveness requirements, such as system availability, dependability, mission reliability, and maintainability may be specified based on the mission profile and operational requirements.



Courtesy of Lifson-Kline Associates

FIGURE A3-1: Flow chart of maintenance/supply support planning.

From an analysis of the mission and operational profiles, a set of logistics profiles and logistic endurance factors can be derived. These indicate when logistic support activities may take place, what may be done at these times, the influence of mission criticality, and other similar items. Analysis of these logistics profiles and endurance factors results in the formulation of an overall logistics concept for the system. This represents a radical departure from past practice in which either no overall logistics concept existed or, if it did exist, amounted essentially to a somewhat nebulous statement that maintenance and supply support should fit in with the current logistics system, largely undefined to the system designer. As a result, a system consisting of a large amount of various equipments designed by different contractors under different and loosely defined ground rules, resulted in a collection of different and often conflicting maintenance and supply support practices.

10.4.3 Plan for Support

Just as we have a Plan for Use of the system, we must have a consistent Plan for Support of the system. This should include consideration of all logistic support elements.

The Plan for Support should establish program requirements to ensure the orderly development, acquisition, implementation, and execution of ILS throughout the life cycle of the system and its related equipment in order to provide maximum material readiness of operational systems and equipments.

The function of the Plan for Support is to identify what support activities will be accomplished, how, when and where they will be accomplished, who will be responsible for their accomplishment, and the support resources required, all consistent with mission and operational requirements.

As shown in Figure A3-1, Logistic Support Analysis consists of two parallel sets of analysis activities--Maintenance Engineering Analysis and Supply Support Analysis. The outputs of the analyses are the Plans for Maintenance and Plans for Supply Support and design requirements for reliability and maintainability. Logistic support analysis and the development of a maintenance and a supply support concept must precede system design. Logistic support analyses should be more than just a set of documented data of the final system hardware for the record. They should be in such form and contain such information so as to be useful for engineering and management decisions and for purposeful and cost-effective tradeoffs throughout the complete systems engineering cycle starting with concept formulation.

The activities involved in performing logistic support analysis will be illustrated with the maintenance engineering analysis path. The supply support analysis activities are similar except for their emphasis on supply rather than maintenance.

10.4.3.1 Maintenance Engineering Analysis During the Planning Period

A flow chart for maintenance engineering analysis is shown in Figure A3-2. Starting with a description of the threat and operational environment, mission and operational analysis is performed. This leads to a set of specific mission requirements and objectives which result in mission and operational demand profiles for each system operating mode. The results of these analyses and profiles will determine what the basic logistic support requirements and objectives must be in order to meet operational requirements.

From an analysis of the logistic support requirements and objectives, logistic profiles and an overall ILS concept can be generated. The ILS concept includes such items as supply support, transportation and handling, and other non-maintenance items as well as maintenance.

Maintenance engineering analysis (MEA) is performed during the planning period for the purpose of defining specific qualitative and quantitative maintenance and maintainability requirements for operational system development during the acquisition period as part of the ILS plan.

Maintenance engineering analysis performed during concept formulation is concerned with applicable operation and maintenance policies and goals, and with their implications on system operation, maintenance activities, maintenance resources, and system configuration (maintainability design) in conjunction with system operational states and missions. This should allow the appraisal of maintenance needs in terms of their effects on system design and system cost, and thus result in the establishment of realistic maintenance and maintainability objectives. Each pertinent policy or goal may eliminate some design approaches from consideration. The total set of policies and goals may interact to restrict severely the number of allowable approaches.

Maintenance policies and goals, from the user's viewpoint, consist of statements, both qualitative and quantitative, concerning operations, maintenance activities, maintenance resources, and effectiveness. These, in turn, when taken in logical combinations by the producer lead to configuration (maintainability) policies and goals and to the resultant implications on system design for maintainability.

MAINTENANCE ENGINEERING ANALYSIS

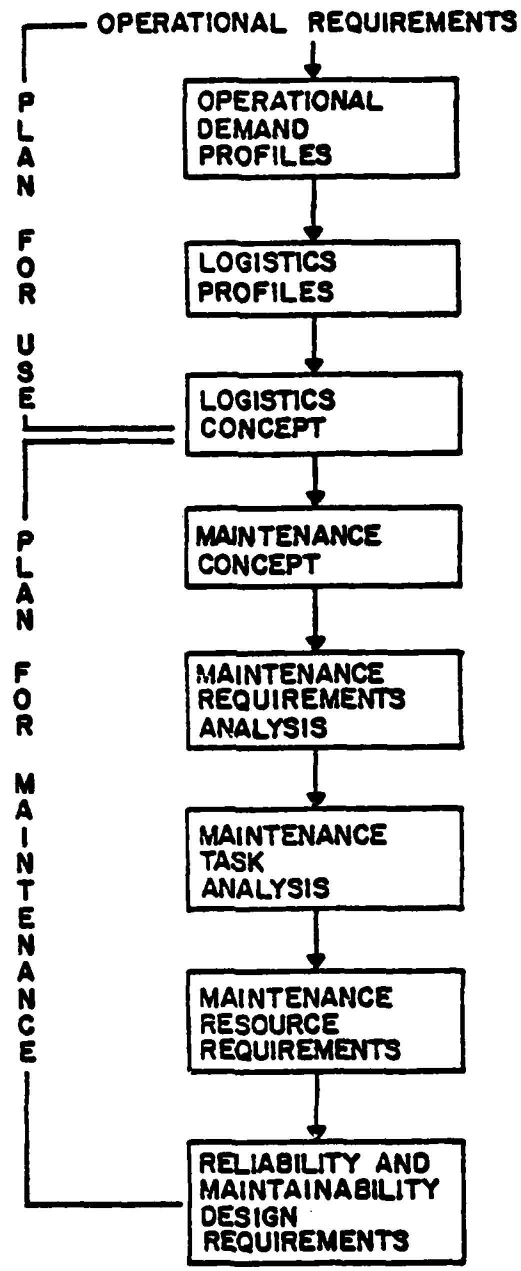


Figure A3-2.

Since the primary purposes for which a system is acquired are intimately related to some set of missions, analysis of the implications of maintenance policies on system design starts logically with mission and operational requirements. Maintenance engineering analysis is, therefore, concerned with the policies and goals pertaining to

1. operational states,
2. maintenance activities,
3. operations and maintenance resources,
4. system effectiveness.

These may be further classified as in Table A3-1.

10.4.3.1.1 Maintenance Concept

The maintenance concept is derived from the system's mission profiles, effectiveness requirements, and operational states, and from the policy statements which form the constraints or boundaries of the support system. It dictates the maintenance activities and resources allowable at the specified maintenance levels, such as, for example, no shipboard preventive maintenance, or only simple checkout and module replacement at the organizational level, or allowable personnel rates and numbers.

Careful consideration must be given to the formulation of the maintenance concept since it establishes the requirements for the maintenance tasks to be performed and resources to be utilized.

The maintenance concept must be established and validated during the earliest phases of the system life cycle, concept formulation and system definition.

10.4.3.1.2 Maintenance Requirements Analysis

After the maintenance concept has been established, maintenance requirements can begin to be detailed. Maintenance requirements are an elaboration of the preventive and corrective maintenance activities to be performed. These are not completely determinable from the maintenance concept. The establishment of reliability and maintainability design requirements also influence the maintenance requirements, and the maintenance requirements may influence the reliability and maintainability requirements as well. They must, therefore, be considered together and cost-effective tradeoffs established.

Maintenance requirements include such items as what is to be periodically inspected and serviced, what items are to be replaced or repaired, what types of test and checkout

TABLE A3-1

CLASSIFICATION OF POLICIES AND GOALS

A. OPERATIONAL STATES
   1. Inactive Period
   2. Scheduled Downtime Period
   3. Operational Demand Period
      a. Standby
      b. Alert
      c. Reaction
      d. Mission
      e. Deactivation

B. MAINTENANCE ACTIVITIES
   1. Preventive Maintenance
      a. Service
      b. Inspection
   2. Corrective Maintenance
      a. Detection
      b. Diagnosis
      c. Correction
      d. Verification
   3. Level
      a. Organizational
      b. Intermediate
      c. Depot

C. RESOURCES
   1. Personnel
      a. Operators
      b. Maintenance Technicians
   2. Equipment
      a. Prime
      b. Support
   3. Facilities
   4. Spares and Supplies
   5. Information

D. EFFECTIVENESS
   1. Downtime
      a. Detection time
      b. Diagnosis time
         (1) Localization
         (2) Isolation
      c. Correction time
         (1) Primary
         (2) Secondary
      d. Verification time
         (1) Alignment and Calibration
         (2) Checkout
   2. Reliability
   3. Availability
   4. Dependability

equipment are required, and the levels at which maintenance is to be performed. Maintenance requirements, therefore, determine to a large extent the logistic support resources which are required.

10.4.3.1.3 Maintenance Task Analysis

Maintenance task descriptions dictate the maintenance action to be taken at each maintenance level (organizational, intermediate, and depot), the numbers and skill levels of personnel who will perform them (operators and/or maintenance technicians) for both preventive (scheduled) and corrective (unscheduled) maintenance, and the frequency or time profiles for performing scheduled maintenance.

10.4.3.1.4 Maintenance Resource Requirements

From the above analyses, preliminary determinations can be made of the total amount of maintenance resources required for the system. These include estimates of

a. Personnel requirements, including personnel ratings, skill levels, and training requirements.

b. Maintenance information and technical data requirements, including maintenance manuals, maintenance engineering analysis records, and other technical data required for maintenance.

c. Support equipment requirements, including tools, test and handling equipment.

d. Maintenance facilities requirements, such as ship shops, tenders, shore shops, depot, and overhaul facilities.

e. Spares and repair parts requirements, including repair/discard criteria and repair level.

10.4.3.1.5 Reliability and Maintainability Design Requirements

Reliability and maintainability design requirements are derivable directly from an analysis of mission and operational requirements and the above analyses. The latter establishes the policies and constraints of the maintenance function, while the former, for example, the specification of operational availability of dependability requirements along with mission time profiles, establishes the direct quantitative and qualitative design requirements for reliability and maintainability.

10.4.3.2 Logistic Support Analysis During the Design Phase

The planning, acquisition and operation of a system is the result of an iterative process. MIL-STD-1388 also emphasizes the iterative nature of logistic support analysis. Thus, logistic support analysis in the design phase starts with the preliminary analyses done in the planning period phases. The preliminary LSA should establish a sound basis for system design including logistic support to allow design and support trade-off decisions to be made as the design unfolds down to the lowest system levels, until finally the design disclosure documentation which includes drawings, specifications, logistic support data, technical data, and the rest is completed.

10.4.4 Logistic Support Models

It is evident that logistic support analysis requires the handling of a significant amount of data and the use of many types of models. Appendix B of reference 9 lists some of these models. Among the types of logistic support models are

1. Repair/discard models
2. Provisioning models
3. Inventory models
4. Manning models

We have already discussed repair/discard models in Chapter 10 as part of the maintainability design decision and have noted the complexity of such models with respect to the amount of data required.

As shown in Figure A3-1, repair parts usage data determined in maintainenance engineering analysis is fed into the supply support analysis, along with parts list information, to allow the preparation of provisioning technical documentation (PTD) and allowance parts lists (APL). A number of provisioning models are in use today for the cost-effective determination of range and depth of spare parts and modules as well as their location levels. Four of these will be discussed here. They are

1. The METRIC family, used by the U.S. Air Force
2. MOD-METRIC, an improved version of METRIC
3. OPUS, used by the Swedish military
4. A Spare Parts Availability Nomograph, used by the U.S. Navy

10.4.4.1 The METRIC Family

The METRIC Family of models, Table A3-2, are based on and developed from the Base Stockage Model (BSM), developed for the U.S. Air Force by the RAND Corporation [Ref. 12]. Each model is designed to be run on a computer.

Of this family of models, METRIC is the best known and most applicable for provisioning problems. It was the first model to consider the problem of multi-echelon, multi-item inventory control. It had some limitations which for some years made it useful only for a specific application (e.g., the USAF support organization) [Ref. 13]. As a result, other models were developed in order to give an answer to these limitations. Still other models were developed using approximations in order to decrease the computation requirements of the model and thus decrease the cost of computer runs with a minor decrease in accuracy. Basically, these models have the same features and assumptions associated with METRIC, but with improved mathematical development [Ref. 14]. These improved models are MOD-METRIC (Multi-Item, Multi-Echelon, Multi-Indenture Inventory System) and the Consolidated Support Model (CSM), a three-echelon, multi-item model for recoverable items [Refs. 15 and 16].

MOD-METRIC has been implemented by the USAF as the method for computing recoverable spare stock levels for the F-15 weapon system. MOD-METRIC is an extention of METRIC which replaces METRIC and permits the explicit consideration of a multi-indenture structure. (NOTE- This is, from the application point of view, the major difference between METRIC and MOD-METRIC. Therefore, in further discussion, we will use generally the acronym METRIC.) Another area in which MOD-METRIC differs from METRIC is in one of the assumptions made in METRIC, namely that items are normally considered to be equally essential, while in MOD-METRIC, because of the introduction of indentured parts structure, the essentiality at each level of items (LRU's and SRU's) may be defined differently. [Ref. 15]

METRIC is a model for determining both requirements and distribution of recoverable items in a two-echelon support organization (Fig. A3-3). The objective of this model is to determine the base and depot stock levels which minimize total expected base level backorders for a specific set of items and bases subject to an investment constraint. [Ref. 17]

Types of Problems

* Optimization of stock levels (depot and bases).
* Evaluation of the expected number of backorders for a fixed/given stock at bases and depot.

TABLE A3-2 Metric Family Models

MODEL	NAME	SHORT DESCRIPTION
BSM	Base Stockage Model	Budget allocation optimization of repairable spare parts used at one base.
SCAM	Source-Coders Cost Analysis Model	Repair/Discard and Repair level decisions.
METRIC	Multi-Echelon Technique for Recoverable Item Control	Base-Depot supply system: - optimization of stock levels - allocation of fixed stock levels - evaluation (C-E) of given allocation of stock levels.
MINE	Multi-Indenture NORS Evaluator	Evaluation of the expected number of aircraft not operationally ready (NORS) due to supply.
RTM	Real-Time-METRIC	Complements METRIC in a centralized or "push" system for recoverable item distribution.
RPM	Repair-Priorities Model	Buy/Repair decisions. A variant of RTM which computes system "need" for each item over a planning period.

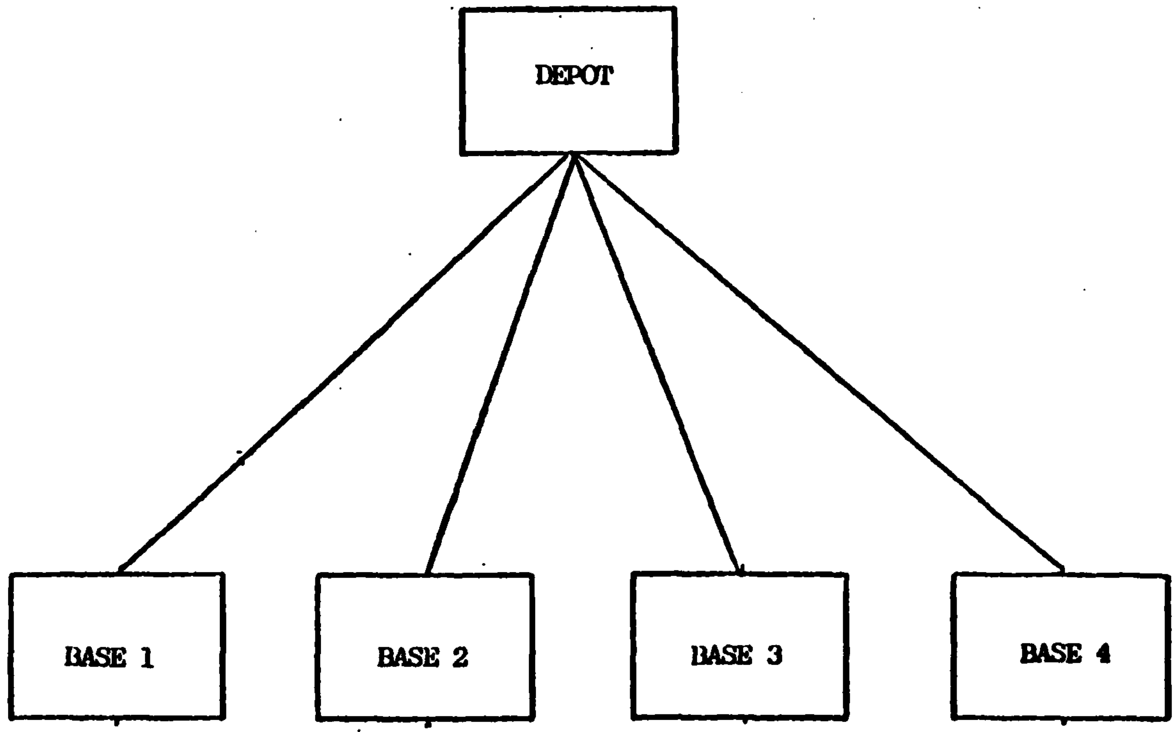


Figure A3-3. An example of maintenance and supply support organization for METRIC model.

* Redistribution/Allocation to bases and depot of a given total stock, such that expected number of backorders is minimized.

These problems are important to solve at different stages of the system life cycle.

Measures of Effectiveness

The choices of C-E target is between

* Total dollars of investment, or
* Expected number of backorders per item.

An intermediate target may be one that reduces both backorders and investment. This can be done by changes in the problem structure and comparison between the results.

Characteristics and Features

The METRIC family of models allows the user the consideration of a Base-Depot supply system for determination of stockage policy of recoverable items which are characterized by high cost/low demand. The model uses past demand data, but combines them with estimates of future program requirements to anticipate buildups or phaseouts. It can also handle, through a Bayesian procedure, initial estimated data with or without past demand. Finally, METRIC provides a device for analysis of alternative support structures, and different levels of support effectiveness depending on the weapon system.

Input Parameters

Various data are required as input parameters to the model. These are the average base and depot repair times for each item, unit costs, certain probability distribution parameters, Not-Reparable-This-Station (NRTS) rates, and average order and ship times. Minimum and maximum stock levels can be specified. A full description of the input data and their preparation can be found in the documentation published by RAND on the METRIC COMPUTERPROGRAM. [Ref. 18]

The input data is determined in three levels:

* By system
* By item
* By item and base.

The computerprogram requirements for the input data format are quite flexible (i.e. the model is not sensitive to input data).

Basic Assumptions

The following assumptions are made:

* The demand for each item is Compound Poisson distributed.

* There is no lateral resupply between bases.
* All failed parts (System/LRS's/SRU's) are repaired.
* A failure of one type of item is statistically independent of those that occur for any other type of item.
* Repair times are known and statistically independent.
* There is no batching of items before repair is started.
* *The level at which repair is performed depends* only on the complexity of the repair (and not on the workload at each level).

10.4.4.2 The OPUS Procedure

The OPUS procedure was developed as a computer-based aid for certain classes of decisions on spare parts provisioning. The main computer model, OPUS, was initially developed by Systecon AB in 1970, a consultant company to the Swedish government. It has been applied to contracts for the Swedish Navy and Air Force Material Departments. In the United States, ITT-Gilfillan has utilized the program, and it has been installed at the Naval Postgraduate School.

The OPUS procedure has been used in a number of applications, among which are electronic equipments for aircraft, helicopters, naval ships, and ground stations, as well as for missiles and aircraft engines. The purposes of these applications have ranged from evaluation of proposals of new equipment to logistic support analysis of systems in the production stage.

The OPUS model was designed to study Systems (end items) with two indenture levels [Ref. 19]: line replaceable units (LRU's) and shop replaceable units (SRU's).

Types of Problems

The OPUS procedure has shown itself to be a flexible and useful analysis tool with regard to the following types of problems [Ref. 20]:

* Cost-effectiveness evaluation of alternative maintenance and support concepts and alternative system configurations.
* Initial procurement of LRU's and SRU's, and their allocation within a support organization.
* Reallocation of given assortment of LRU's and SRU's.
* Replenishment procurement of LRU's and SRU's.
* Reallocation of a given assortment of LRU's and SRU's and initial procurement of new types of LRU's and SRU's.

Measures of Effectiveness

OPUS VII offers the user the option of selecting one of the following Measures of Effectiveness (MOE), depending upon the specific type of problem being studied [Ref. 21]:

* Probability of successful mission.
* System operational availability.
* Mean waiting time for a spare part.
* Risk of shortage of a spare, when it is demanded.

OPUS Characteristics

OPUS VII has the following special characteristics:

* It is capable of handling a mixture of different types of LRU and SRU, which may be parts of different kinds of systems, and the associated set of rules on where these spares may be stocked and repaired within a given maintenance and support organization. Measures of effectiveness (MOE) is considered as a function of all the individual stock levels, given all the other relevant parameters which describe the activities and the support flow of the maintenance organization. The measure of cost is the total investment in LRU's and SRU's, which are to be distributed in the maintenance organization. Points on a C-E curve are established according to the following optimization criteria:

For a *given* value of the total investment, determine values on all stock levels such that the measure of effectiveness is minimized or maximized

Input Data

1. System Data

   The following types of end item data have to be specified:

   SRU-Data
   * Number of different types of SRU
   * For each type: replacement rates, and unit price

   LRU-Data
   * Number of different types of LRU
   * For each type: replacement rates, and unit price
   * For each type that is modularized into SRU's: identification of those types of SRU it contains, and the number of units of every such type

   System-Data
   * Number of different types of systems
   * For each type: identification of those types of LRU it contains, and the number of units of every such type

2. Support Organization Data

Demand Generating Stations (DGS)

They are shown as DGS-1 through DGS-4 in Figure A3-4. The following types of input-data must be specified for each Demand Generating Station, DGS

* A reference to the nearest superior Support Station, SS.
* Identification of the different types of systems allocated to the DGS, and the number of each. Each system is also given a specific "utilization rate," as mentioned above.
* Fault location time.
* Time to repair the system by removing and replacing a defective LRU including subsequent check-out time.
* Time to have a spare unit delivered from the superior Support Station, given no shortage exists.

Support Station (SS)

These are shown as SS-1 through SS-8 in Figure A3-4. The following types of input-data must be specified for each Support Station, SS

* A reference to one or several other Support Stations, to which propagated demands are addressed.
* A discrete propagated demand probability distribution, defined on those other Support Stations.
* Identification of the different types of LRU and/or SRU which may be kept in stock. Each of these types has a specific repair-factor, which is the proportion of defective units that are to be repaired at this station.
* Fault isolation time for every type of LRU and SRU.
* Time for removing and replacing a defective unit, including subsequent check-out time.
* Time to repair a LRU or SRU, if repaired at this station.
* Time to have a spare unit delivered from the superior Support Station, given no shortage exists there.

End Support Station (ESS) (Depot Level)

This is shown as Depot in Figure A3-4. An End Support Station is similar to a Support Station, with the exception that demand is not propagated to any other Support Station.

For large problems that OPUS VII cannot handle in a single run, the system can be divided to several sub-systems

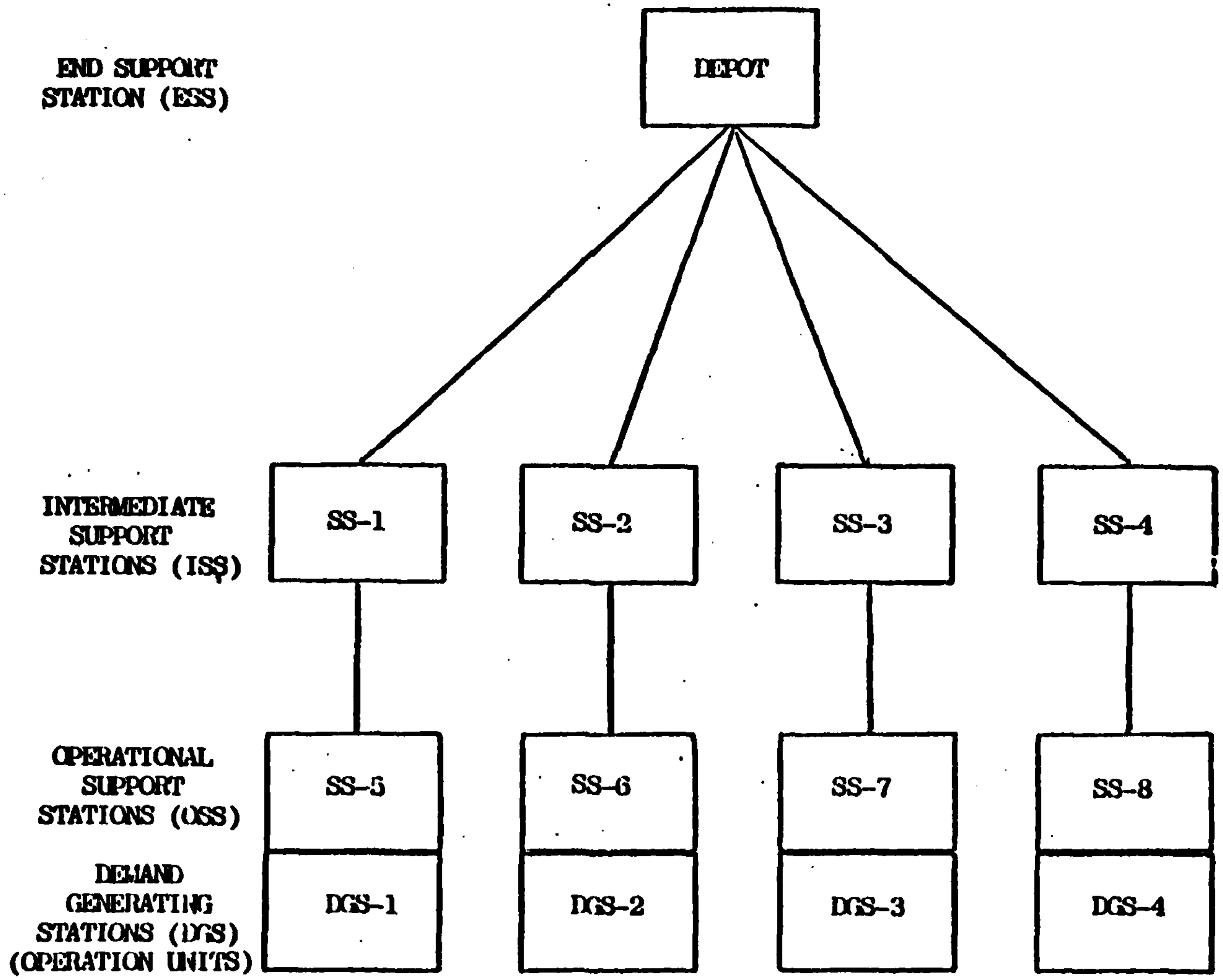


Figure A3-4. An example of maintenance and supply support organization for OPUS model.

(at the LRU's level). The output for each sub-system from the OPUS VII program is used as an input to a program named OPUS VII-W, which gives the total results for the original problem.

10.4.4.3 <u>A Comparison between OPUS and MOD-METRIC</u>

Table A3-3 gives a comparison of the features between OPUS and MOD-METRIC. Since ITT-Gilfillan is a user of both of these models, we are indebted to them for providing information to allow us to summarize the major differences between these two models from an application point of view. In general, MOD-METRIC appears to give a solution which is about 20 or 30 percent more "expensive" (total investment) than OPUS for the same situation. The reason is that the assumption about the demand distribution in METRIC is more realistic although it requires more data.

<u>Data Base Comparison</u>

MOD-METRIC data base format is by far the most straightforward and is the easiest to implement. This format would be cumbersome if large systems are being analyzed where commonality exists between SRU's.

The OPUS data base structure was found to be more descriptive and flexible in comparison to MOD-METRIC. For example, changing parameters for an SRU in the OPUS format requires changing one record (one 80 column card) whereas to make the same change in MOD-METRIC requires changing two records. While this may seem to be small, when there is a large, complex system structure requiring large amounts of data, data base management would be simpler and less time consuming when using OPUS.

<u>Analysis Techniques</u>

MOD-METRIC optimizes one LRU/SRU group at a time for a given Maintenance and Support (M&S) organization. The M&S organization must be changed for each LRU/SRU group along with all program control parameters. The main disadvantage of this is the non-optimization between LRU/SRU groups and the inability to sense this relationship in an overall system measure of effectiveness.

OPUS is a more sophisticated model offering flexibility in M&S organization description and hardware configuration alternatives. OPUS optimizes the entire problem for any of several measures of effectiveness while MOD-METRIC can only optimize one LRU/SRU group. The optimization techniques used in OPUS allow for a more rapid analysis versus the "number crunching" techniques used in MOD-METRIC.

Table A3-3. Characteristic Comparison between OPUS and METRIC.

SUBJECT	OPUS	METRIC	REMARKS
1. Number of Echelons (Support Organization)	Multi	Two(1)	(1) CSM has 3 echelons
2. Number of Indentures (Items)	Two	Two(2)	(2) Only in CSM and MOD-METRIC
3. Data Preparation	Requires more familiarization for user to control the model	Easier for a beginner	
4. Order of Input	Sensitive(3)	Flexible	(3) The input data drive the program
5. End Item Operation Hours	Included	Included	
6. Total Cost of Operation (LCC)	Not included	Included	
7. Initialization of provisioning	Preferred	--	
8. Evaluation and Redistribution of fixed stock	--	Preferred	
9. Optimal Solution Description	Up to 100 points on each C-E curve	A single point for each set of parameters(4)	(4) The budget or the expected backorders are given

Both models have actually been used to solve provisioning problems. METRIC is more theoretically sophisticated than OPUS, while OPUS is more readily applied. The OPUS model seems to be better suited to the logistician's needs. Logistic effects of hardware design and deployment can be readily quantified in spares investment for a given availability, waiting time, NORS or risk or shortage enabling OPUS to be used not only as a provisioning model but also as a "design tool."

10.4.4.4 Spare Parts Availability Nomograph

A non-computer spare part availability model, developed for use by the U.S. Navy, is now described. [Refs. 9, 21] It can be used to calculate, as a function of part reliability, the probability that a spare part will be available when required. This expression, based on the Poisson distribution, is exact when failure rates are exponentially distributed. For other types of failure distributions, the expression provides a good approximation of spare part availability.

Expression for Spare Part Availability

$$P = \sum_{n=0}^{n=s} \frac{(R^K)\ [-K\ (\ln R)]^n}{n!} \qquad (1)$$

where

P is the probability of having a spare part when required for a particular part type.

S is the number of spare parts carried in stock.

R is the reliability (probability of survival).

K is the number of parts used of a particular part type (part population).

lnR is the natural logarithm of R.

Nomograph for Determining Spare Part Requirements. Using expression (1) for calculate spare part availability can be cumbersome and time consuming, particularly when the design information available are failure rate and re-provisioning intervals rather than a specified or estimated reliability. The nomograph shown in Figure A3-5 can be used to determine spare part availability in lieu of expression (1). The nomograph simplifies and facilitates the task of determining spare part requirements since the information required to use it is generally available to the designer. In addition, the nomograph is inherently flexible. The nomograph provides not only solutions to basic spare part availability questions,

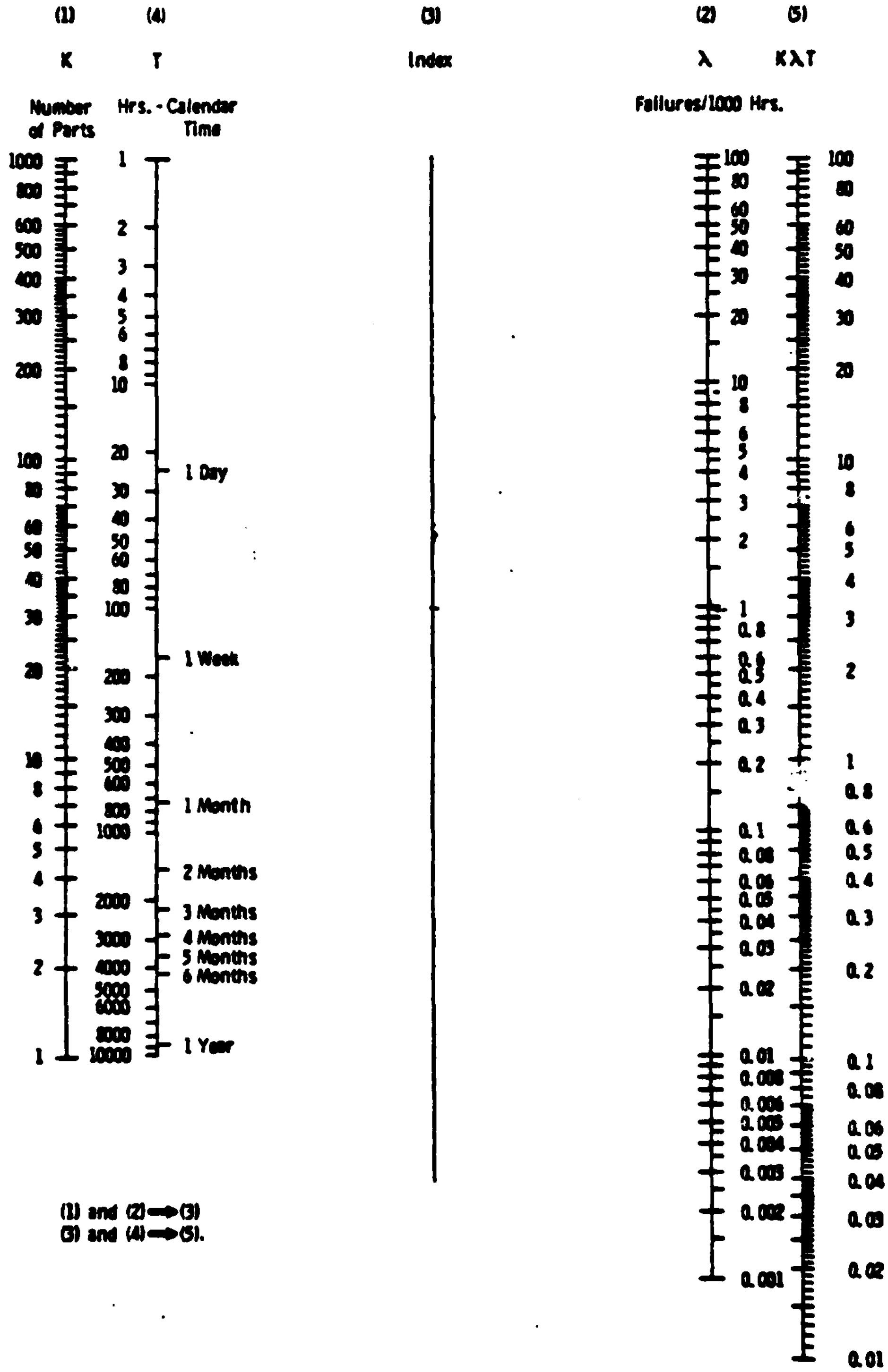


Figure A3-5. Spare Part Requirement Nomograph (Sheet 1 of 2)

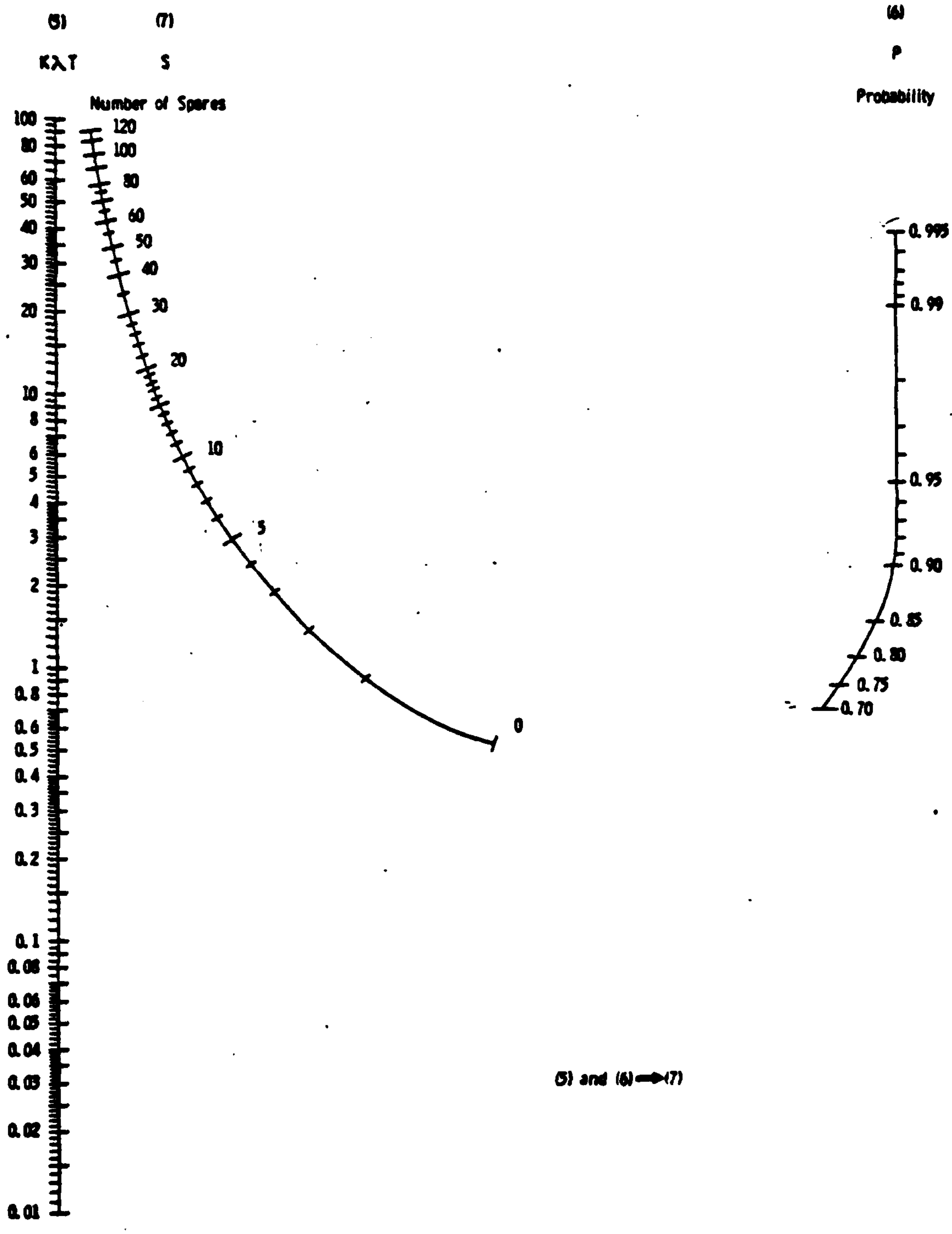


Figure A3-5. Spare Part Requirement Nomograph (Sheet 2 of 2)

but judicious application of the nomograph also provides comparative information that can be an aid in making decisions on the feasibility of increased or decreased spares provisioning.

To use the nomograph, any four of the following must be known:

K Is the number of parts used of a particular part type (part population).

T The number of equipment operating hours between spare part provisioning (if operated continuously, calendar periods can be used).

λ Failure rate of the part in terms of failures per 1000 hours of operation.

P Probability of having a spare part when required.

S The number of spare parts carried in stock.

The following examples illustrate the use of the nomograph.

Example 1. An equipment contains 20 parts of a particular part type with a failure rate of 0.1 failures for 1000 hours of operation. The equipment operates 24 hours per day and spare parts are restocked every 3 months. How many spares should be carried in stock to ensure a 0.95 probability of having a spare when required?

Step 1.[1] Using sheet 1 of Figure A3-5, draw a line from K = 20 on scale 1 to λ = 0.1 on scale 2. This line will intersect the index line (scale 3).

Step 2.[1] Draw a line from T = 3 months on scale 4 through the previous intersection with scale 3 to the K λ T scale (scale 5). Note the graduation marking at the point

---

[1]By taking the product of K, λ and T, the first two steps for determining spare part requirements can be performed without the aid of the nomograph. When this is done, sheet 1 of the nomograph need not be used. However, care must be exercised to ensure that proper units are used. The failure rate, λ must be in failures per hour, and the operating hours between spare part provisioning, T, must be in hours. If the failure rate is given in failures per 1000 hours, a multiplier of 10^3 must be used; if given in percent failures per 1000 hours, a multiplier of 10^5 must be used.

where this line intersects scale 5. In this example, it is approximately 4.4.

Step 3. Using sheet 2 of Figure A3-5, draw a line from 4.4 on scale 5 to 0.95 on the P scale (scale 6).

Step 4. Read the required number of spares at the point where the line from scale 5 to scale 6 intersects the S curve (scale 7), and round up to the next whole number. In this example, 8 spares are required.

Example 2. An equipment contains 50 parts of the same part types with a failure rate of 0.4 failures per 1000 hours of operation. Fifty percent spares (25 spare parts) are to be provided with restocking to occur after 1000 hours of operation. What is the probability of having a spare part when required?

Step 1.[1] Using sheet 1 of Figure A3-5, draw a line from $K = 50$ on scale 1 to $\lambda = 0.4$ on scale 2. This line will intersect the index line (scale 3).

Step 2.[1] Draw a line from $T = 1000$ hours on scale 4 through the previous intersection with scale 3 to the $K \lambda T$ scale (scale 5). Note the graduation marking at the point where this line intersects scale 5. In this example, it is 20.

Step 3. Using sheet 2 of Figure A3-5, draw a line from 20 on scale 5 through $S = 25$ on S curve (scale 7), to the probability scale (scale 6).

Step 4. Read the probability of having a spare part when required from the intersection with scale 6. In this example, the probability is approximately 0.88.

The flexibility of the nomograph can be illustrated by the preceding examples. In the first example, for 20 parts of the same part type, 8 spares are required to ensure a 0.95 probability of having a spare when required. If standardization were increased so that 20 similar parts (which would also have to be supported by 8 spares) were made identical to the 20 parts in the example, there would then be 40 parts of the same part type, requiring 14 spares to ensure a 0.95 probability of having a spare when required. The nomograph provides an immediate picture of how increased standardization can reduce the overall spares requirement. In this example, the spare requirement could be reduced by two while still retaining the same probability of having a spare when required. The nomograph shows that increasing the number of spares by 7 (for a total of 32 spares), the probability of having a spare

when required is increased to 0.995. This is within 0.005 of a probability of 1. As we approach unity, spare part availability increases asymptotically, consequently, any further increase in the number of spares would not significantly increase the probability of having a spare when required.

10.4.4.5 <u>Other Models</u>

Inventory models are some of the oldest types of logistics models which have been used. They are in use in many commercial as well as government enterprises. They vary in complexity from models which have a regular, constant demand and replenishment interval to very complex models with varying demands, reorder times, safety requirements, and other factors. Inventory models are discussed in most elementary operations research texts. Reference 9 also has a discussion of the simple inventory problem.

Manning models are also used in logistic support analysis to help determine total manning requirements for maintenance and support personnel. In military applications, such models are also used to determine total manning and skill requirements. They are typically simulation models.

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